MECHANICAL PROPERTIES OF SALT AND [redacted] FROM AKZO NOBEL SALT INC. WELL NO. 58 AND NYSEG WELL NO. 59, SENECA LAKE STORAGE PROJECT, WATKINS GLEN, NEW YORK

Topical Report RSI-0668

by

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EXECUTIVE SUMMARY

INTRODUCTION

New York State Electric & Gas Corporation (NYSEG) is developing its Seneca Lake Storage Project near Watkins Glen, New York, to improve natural gas supply options for central New York. The project includes converting an existing solution-mined cavern owned by Akzo Nobel Salt to compressed natural gas storage service. The cavern, developed in the bedded salts of New York State, was previously used for brine production and later for liquefied petroleum gas (LPG) storage service.

NYSEG contracted with PB-KBB Inc. for overall design and construction of the natural gas storage project. In the summer of 1995, PB-KBB subcontracted with RE/SPEC Inc. to perform a geomechanical analysis of the proposed storage cavern to assess the structural stability of both the salt and nonsalt strata overlying and surrounding the cavern. As part of this subcontracted effort, RE/SPEC performed laboratory tests on both the salt and nonsalt rocks surrounding the cavern. The purpose of the testing was to determine mechanical properties such as strength and dilational stress states and deformational characteristics such as creep and elastic deformation for use in the geomechanical analysis. Detailed results of the testing are provided in this report and summarized in this Executive Summary.

TECHNICAL APPROACH

The technical approach employed by RE/SPEC Inc. comprised two phases of testing. In the first phase, mechanical properties tests were performed on salt recovered from Akzo Nobel's Well No. 58, originally drilled and cored in late 1992. In the second phase, mechanical properties tests were performed on both salt and nonsalt [redacted] rocks recovered from NYSEG Well No. 59, a new well was drilled and cored especially for this project in late 1995. The Well No. 58 salt testing was performed early in the laboratory program to develop preliminary mechanical properties for comparison with properties measured for other salts used successfully for natural gas storage. Based on these early test results, additional testing was performed on Well No. 59 salt and nonsalt specimens to supplement and confirm the earlier database and to obtain mechanical properties for nonsalt rocks from high-quality field samples. The second phase of testing was completed in December 1995.

Nonsalt [redacted] Testing

Two types of mechanical properties tests were performed on the nonsalt rocks recovered from Well No. 59 and included:

1. Brazilian indirect tension tests.
2. Confined quasi-static compression tests.

Eleven Brazilian indirect tension tests were performed to measure the apparent tensile strength of the dolostones from Well No. 59. The indirect tension tests provided estimates of apparent tensile strength which could be used for comparison with the tensile strength of other rock types. Also, if tensile stresses are predicted in an underground geomechanical model, the apparent tensile strength can be used to estimate the rock's propensity for failure. In addition to the indirect tension tests, six confined quasi-static compression tests were performed on the dolostone from Well No. 59. The tests were performed using the standard triaxial compression (STC) test configuration in which a constant confining pressure is first applied to all surfaces of a test specimen and then an axial load is incrementally applied to the ends of the specimen until failure occurs. Three confining pressure levels were examined including [redacted] psi. The results of the STC tests were used to determine (1) ultimate compressive strength, (2) Young's modulus, and (3) and Poisson's ratio.

Salt Testing

Three types of mechanical properties tests were performed on the salt core recovered from Well No. 58 and Well No. 59 and included:

1. Brazilian indirect tension tests.
2. Confined quasi-static compression tests.
3. Confined creep tests.

A total of 11 Brazilian indirect tension tests were performed on salt specimens including 5 from Well No. 58 and 6 from Well No. 59. The purpose of the testing was identical to that described above for the indirect tension testing of nonsalt rocks.

Six confined quasi-static compression tests were also performed on salt specimens including three each from Well No. 58 and Well No. 59. The tests were performed using the constant mean stress configuration in which the confining pressure was decreased while the axial stress was simultaneously increased at rates necessary to maintain a constant mean stress (i.e., the average of the axial stress plus two times the confining pressure). The mean stress levels investigated during the testing were [redacted]. In contrast to the STC tests performed on nonsalt rocks, the constant mean stress tests were used exclusively to estimate the stress states that produce salt dilation (volume expansion caused by the development of microfractures).

Three confined creep tests were performed on salt from each of the two wells, Well No. 58 and Well No. 59, for a total of six tests. The tests were performed primarily to evaluate the time-dependent deformational behavior of the salt; but the data acquired during the testing were also used to further characterize the dilational characteristics of the salt and to estimate two elastic properties, Young's modulus and Poisson's ratio. Each test comprised three separate stages in which the confining pressure, stress difference (difference between the axial stress and confining pressure), and temperature were held constant for the duration of the stage. The first stage of each test was performed at a temperature of [redacted], a confining pressure of [redacted] psi, and a stress difference of either [redacted] In subsequent stages of each test, the confining pressure was successively lowered and the temperature and stress difference were maintained at the levels prescribed for the first stage. The data from the first stages of each test were used to develop a creep material model for the salt, while the data from the subsequent stages were used to investigate the propensity of salt to dilate at different stress states. Data collected at the end of several of the stages (during unloading of the stress difference) were used to estimate the elastic properties of the salts.

RESULTS

[redacted]

Eleven Brazilian indirect tension tests were performed on [redacted] recovered from Well No. 59. The results indicated that the apparent tensile strength of the [redacted] ranged from [redacted] with a mean and standard deviation of [redacted] respectively.

Six confined quasi-static compression tests were also performed on [redacted] from Well No. 59. As expected, the compressive strength of the [redacted] increased with confining pressure. This trend was quantified mathematically using the following model:

[redacted]

where [redacted] are the [redacted] and the [redacted] of the [redacted] respectively. In practical terms, these two quantities represent shear stress and mean stress, respectively. The data acquired from the quasi-static tests were also used to estimate two elastic properties, Young's modulus, E, and Poisson's ratio, ν. Young's modulus is a measure of how much axial strain is recovered when a specimen is unloaded (analogous to the deformation recovered when a spring is unloaded) and ranged from [redacted] with a mean and standard deviation of [redacted] respectively. Poisson's ratio is a measure of how much lateral strain is recovered when a specimen is unloaded and ranged from [redacted] with a mean and standard deviation of [redacted] respectively.

Salt

The apparent tensile strengths of salt specimens from Well No. 58 and Well No. 59 were also determined using the Brazilian indirect tension test. Five tests were performed on Well No. 58 salt and tensile strengths ranged from [redacted] with a mean and standard deviation of [redacted] respectively. Six tests were performed on Well No. 59 salt. The tensile strengths in these tests were, on average, [redacted] than for the Well No. 58 tests with a mean of [redacted] However, the range [redacted] and standard deviation [redacted] in the tensile strengths of Well No. 59 salt were [redacted] than for the Well No. 58 salt. [redacted]

Six confined quasi-static compression tests were performed on salt specimens from Well No. 58 and Well No. 59. The data acquired in these tests were combined with data acquired in the multistage creep tests to assess the propensity for the salt to dilate under various stress states. [redacted]

[redacted]

The six creep tests performed on the Well No. 58 and Well No. 59 salt specimens provided data from which the time-dependent deformational characteristics of the salt could be determined. The results indicated, as expected, that the creep strains are strongly influenced (in a nonlinear manner) by the imposed stress difference with much larger strains corresponding to higher levels of stress difference. [redacted]

Unload data acquired at the end of several of the creep stages were used to estimate two elastic properties; i.e., Young's modulus, E, and Poisson's ratio, ν. The range in values for E and ν are [redacted] respectively. The mean and standard deviation for Young's modulus are [redacted] respectively; while the mean and standard deviation for Poisson's ratio are [redacted], respectively. *The elastic properties determined for the Well No. 58 and Well No. 59 salt specimens are* [redacted]

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1.0 INTRODUCTION

1.1 BACKGROUND

New York State Electric & Gas Corporation (NYSEG) is developing its Seneca Lake Storage Project near Watkins Glen, New York, to improve natural gas supply options for central New York. The project includes converting an existing solution-mined cavern owned by Akzo Nobel Salt to compressed natural gas storage service. The cavern, developed in the bedded salts of New York State, was previously used for brine production and later for liquefied petroleum gas (LPG) storage service.

NYSEG contracted with PB-KBB Inc. for the overall design and construction of the natural gas storage project. An important aspect in the successful design of the project is an assessment of the structural stability of the salt and nonsalt strata overlying and surrounding the cavern. Although the cavern has been used successfully in the past for brine production and LPG storage, it has not been subjected to the ranges in internal pressure that accompany natural gas storage. For example, in brine production and LPG storage, internal pressures in the cavern are essentially static (i.e., constant) and are typically near the pressure resulting from a brine column extending from the ground surface to the depth of the cavern. In natural gas storage however, the pressures exerted on the walls, floor, and roof of a cavern can vary considerably with time as gas is either injected into or withdrawn from the cavern during normal operating cycles. The gas pressure ranges from the design minimum pressure (often near the pipeline pressure at the wellhead) to the design maximum pressure, which is generally regulated by state agencies. These changes in internal pressure must be considered in the structural stability assessment.

PB-KBB subcontracted the structural stability analyses of the storage cavern to RE/SPEC Inc. The structural stability of the salt and nonsalt strata overlying and surrounding the cavern depends primarily on the following factors:

- Preexisting in situ state of stress in the region.
- Strength and deformation characteristics of the salt, nonsalt interbeds, and overlying strata.
- Operating natural gas pressure range in the cavern.

In addition, the analyses require information on site stratigraphy and cavern geometry. As part of its subcontracted efforts, RE/SPEC Inc. was required to determine regional in situ stress states, to perform laboratory testing of salt and nonsalt rocks from near the cavern, and to provide core logging and supervision services to define stratigraphy and to identify rock units for testing. The purpose of this report is to present the results from RE/SPEC's laboratory testing program conducted on salt and nonsalt cores recovered from near the proposed storage cavern. Results of the structural stability assessment, including estimation of regional in situ stresses and operating gas pressures, are provided in a separate technical report [Osnes and Eyermann, 1996]. Two other technical reports prepared by RE/SPEC [Vogt and Foster, 1995; Vogt, 1995] have documented the results of geologic logging of two wells (Well No. 58 and Well No. 59) located near the project.

1.2 SCOPE

The rock mechanics testing program conducted by RE/SPEC Inc. was performed in two phases. In the first phase, mechanical properties testing was performed on salt core recovered from Akzo Nobel's Well No. 58 originally drilled and cored in late 1992. In the second phase, mechanical properties testing was performed on both salt and nonsalt (i.e., [redacted]) cores recovered from NYSEG Well No. 59, a new well drilled and cored especially for this project in late 1995. The Well No. 58 salt testing was performed early in the laboratory program to develop preliminary mechanical properties for comparison with properties measured for other salts and to qualitatively assess the suitability of the cavern for natural gas storage. No nonsalt rocks from this previously cored hole were tested because of the possible sensitivity of results to historical moisture changes that the nonsalt core may have experienced. Based on the preliminary results of the Well No. 58 testing, additional testing was performed in the second phase on both salt and nonsalt rocks from the new well to supplement and confirm the earlier salt testing results and to obtain mechanical properties for the nonsalt rocks.

1.2.1 Nonsalt [redacted] Testing

Two types of mechanical properties tests were performed by RE/SPEC on the nonsalt [redacted] core recovered from Well No. 59 and included:

1. Brazilian indirect tension tests.
2. Confined quasi-static compression tests.

A total of 11 Brazilian indirect tension tests were performed on nonsalt [redacted] specimens from Well No. 59. The indirect tension tests provided estimates of the apparent tensile strength of the nonsalt rocks which can be used in comparison with the tensile strength of rock from other locations. Also, if tensile stresses are predicted in an underground structural model, the apparent tensile strength can be used to estimate the rock's propensity for failure.

Six confined quasi-static compression tests were performed on nonsalt specimens from Well No. 59. The tests were performed by increasing the axial stress while maintaining the confining pressure at levels equal to either [redacted] The axial stress was increased until the specimen failed (i.e., reached a peak or ultimate axial stress level). This type of quasi-static compression test is referred to as a standard triaxial compression (STC) test. The results of the tests were used to determine (1) the ultimate compressive stress, (2) Young's modulus,

E, and (3) Poisson's ratio, ν. Each of these quantities is used directly in modeling underground structures, in comparison between rock types, and in an examination of variations in rock properties from one location to another.

1.2.2 Salt Testing

Three types of mechanical properties tests were performed by RE/SPEC on the salt cores recovered from Well No. 58 and Well No. 59 and included:

1. Brazilian indirect tension tests.
2. Confined quasi-static compression tests.
3. Confined creep tests.

A total of 11 Brazilian indirect tension tests were performed on salt specimens including 5 from Well No. 58 and 6 from Well No. 59. The purpose of the testing was identical to that described above for the indirect tension testing of nonsalt core.

Six confined quasi-static compression tests were also performed on salt specimens including three from each of the two wells. The tests were performed by simultaneously increasing the axial stress and decreasing the confining pressure at rates to maintain a constant mean stress (i.e., the average of the axial stress plus two times the confining pressure) of either [redacted]. This type of quasi-static compression test is referred to as a constant mean stress (CMS) test. In contrast to the STC tests, the results of the CMS tests were used to estimate the stress states that produce salt dilation (volume expansion caused by the development of microfractures).

Three confined creep tests were performed on salt specimens from each of the two wells, Well No. 58 and Well No. 59, for a total of six tests. The tests were performed primarily to evaluate the time-dependent deformational behavior of the salt, but the data acquired during the testing were also used to further characterize the dilational characteristics of the salt and to estimate two elastic properties, Young's modulus, E, and Poisson's ratio, ν. Each test comprised three separate stages in which the confining pressure and the stress difference (axial stress minus confining pressure) were held constant for the duration of the stage. The first stage of each test was performed at a temperature of [redacted] a confining pressure of [redacted] and a stress difference of either [redacted] The stress difference was selected to encompass the range of stress differences expected to occur in the salt near the cavern, while the confining pressure was selected to simulate the lithostatic stresses in the salt at the cavern midheight. Data acquired from the first stage of each test were used to develop a material model describing the creep behavior of the salt [Osnes and Eyermann, 1996]. In subsequent stages of each test, the confining pressure was lowered and the stress difference and temperature were maintained at the levels prescribed for the first stage. The data acquired in these subsequent stages were used to assess the stress states at which the volumes of the salt specimens increased with time, thereby, indicating salt dilation or microfracturing. Data collected as the test specimens were unloaded were used to estimate the two elastic moduli, E and ν.

1.3 REPORT ORGANIZATION

In addition to this introduction, this report contains six chapters and three appendices. In Chapter 2.0, the sample acquisition, preparation, and identification methods are described. Chapter 3.0 gives the test procedures used during the study. Chapters 4.0 and 5.0 provide results from the mechanical properties testing of the nonsalt [redacted] and salt specimens, respectively. A summary is provided in Chapter 6.0 which is followed by a list of cited references in Chapter 7.0. Appendix A comprises stress-strain plots for the STC tests on nonsalt specimens from Well No. 59, Appendix B comprises stress-strain plots for the CMS tests on salt specimens from Well No. 58 and Well No. 59, and Appendix C comprises strain-time plots for the creep tests on salt specimens from Well No. 58 and Well No. 59.

2.0 SAMPLE ACQUISITION AND SPECIMEN IDENTIFICATION

2.1 SAMPLE ACQUISITION

The rock cores used in the preparation of laboratory test specimens were obtained from two wells located near the proposed storage cavern site; i.e., Akzo Nobel's Well No. 58 drilled and cored in late 1992 and NYSEG Well No. 59 drilled and cored in late 1995. The cores from Well No. 58 received by RE/SPEC Inc. on July 9, 1995, included selected portions of salt from two of the nine core runs performed in Well No. 58; i.e., Run No. 2 and Run No. 3 which correspond to depths ranging from [redacted] respectively. All of the rock cores recovered from the five core runs performed in Well No. 59 were shipped to RE/SPEC Inc. and received on October 26, 1995. These core runs provided continuous rock cores from a depth of [redacted] The cores were recovered from two geologic formations as follows:

[redacted]

The nonsalt rocks used in the laboratory testing program have been described as [redacted] by Vogt and Foster [1995] and by Vogt [1995]. This nomenclature will be used throughout the remainder of this report when referring to the nonsalt rocks.

Upon receipt, the field cores designated for testing were inspected for shipping damage by laboratory personnel and then logged into RE/SPEC's core storage facilities along with the other cores not used for testing. Sample logging was performed under RE/SPEC Test Procedure TP-01, RSI Standard Procedure for *Sample Acquisition, Storage, and Shipping, Rev. 3.* No shipping damage was observed during the inspection. The cores from both shipments were contained within 6-inch-diameter, Schedule 40 PVC tubes and were protected from damage by bubble wrap and plastic sleeving materials.

2.2 TEST SPECIMEN PREPARATION

Portions of the field core were selected from inventory and subsequently machined to produce right-circular cylindrical specimens for the mechanical properties testing. All specimen preparation activities were performed under RE/SPEC Test Procedure TP-02, RSI Standard Procedure for *Rock Specimen Preparation, Rev. 4.* Although only one procedure covers the preparation process for all rock types, two somewhat different techniques were used in preparing the specimens from the salt and [redacted] cores, respectively. Brief descriptions of these techniques are given below along with a description of the method used to identify each specimen.

2.2.1 Salt Specimens

The machining operation for the salt specimens was performed in two steps. In the first step, the field cores were dry-cut to approximate length using an ordinary band saw. In the second step, the cores were placed in a lathe where the diameters were turned down and the ends were finished flat and parallel using carbide tooling. The diameters were turned down to remove irregularities and pits that may have resulted from the field coring operation. Typically, only about [redacted] was removed from the diameter of each specimen, so the nominal diameter of all salt specimens was [redacted]. After the finishing operation was completed, the dimensions of each specimen were accurately determined using micrometers and a height gage.

All of the finished salt specimens used in the mechanical properties testing are identified in Table 2-1. In addition to the specimen identification number (described in Section 2.2.3), Table 2-1 gives the depth interval, well number from which the cores were recovered, and the specimen dimensions. The specimens having nominal length-to-diameter ratios (L:D) of 2 were used for the confined quasi-static compression and confined creep testing. The specimens having nominal L:D ratios of 0.5 were used in the Brazilian indirect tension testing.

2.2.2 [redacted] Specimens

The machining operation for the [redacted] specimens was performed in three steps. In the first step, the field cores were again dry-cut to approximate length using an ordinary band saw. In the second step, the cores were mounted in a vertical milling machine equipped with a standard rock coring barrel and were subcored to obtain samples with [redacted] diameters. The subcoring operation was performed with brine which was used both to remove the rock cuttings and to cool the coring barrel. In the third step, the subcored samples were placed in a lathe and their ends were finished flat and parallel using carbide tooling. As with the salt specimens, the dimensions of each specimen were accurately determined using micrometers and a height gage.

All of the finished [redacted] specimens used in the mechanical properties testing are identified in Table 2-2. Included in the table are the specimen identification number, the depth interval from which the cores were recovered, and the specimen dimensions. The specimens having nominal L:D ratios of 2.5 were used for the confined quasi-static compression testing. The specimens having nominal L:D ratios of 0.5 were used in the Brazilian indirect tension testing.

Table 2-1. Salt Specimens From Well No. 58 and Well No. 59, Seneca Lake Storage Project, Watkins Glen, New York

Specimen I.D.	Well No.	Depth Interval (feet)	Specimen Length (inches)	Specimen Diameter (inches)
Length-to-Diameter — L:D = [redacted]				
WG/58/4/1	58	[redacted]	[redacted]	[redacted]
WG/58/6/1	58	[redacted]	[redacted]	[redacted]
WG/58/6/2	58	[redacted]	[redacted]	[redacted]
WG/58/7/1	58	[redacted]	[redacted]	[redacted]
WG/58/7/2	58	[redacted]	[redacted]	[redacted]
WG/58/7/3	58	[redacted]	[redacted]	[redacted]
WG/59/77/2	59	[redacted]	[redacted]	[redacted]
WG/59/77/3	59	[redacted]	[redacted]	[redacted]
WG/59/77/4	59	[redacted]	[redacted]	[redacted]
WG/59/78/1	59	[redacted]	[redacted]	[redacted]
WG/59/78/2	59	[redacted]	[redacted]	[redacted]
WG/59/78/7	59	[redacted]	[redacted]	[redacted]
Length-to-Diameter — L:D = [redacted]				
WG/58/1/2	58	[redacted]	[redacted]	[redacted]
WG/58/4/2	58	[redacted]	[redacted]	[redacted]
WG/58/6/3	58	[redacted]	[redacted]	[redacted]
WG/58/8/3	58	[redacted]	[redacted]	[redacted]
WG/58/8/4	58	[redacted]	[redacted]	[redacted]
WG/59/78/3/1	59	[redacted]	[redacted]	[redacted]
WG/59/78/3/2	59	[redacted]	[redacted]	[redacted]
WG/59/78/3/3	59	[redacted]	[redacted]	[redacted]
WG/59/78/3/4	59	[redacted]	[redacted]	[redacted]
WG/59/78/5/2	59	[redacted]	[redacted]	[redacted]
WG/59/78/5/3	59	[redacted]	[redacted]	[redacted]

Table 2-2. [redacted] Specimens From Well No. 59, Seneca Storage Project, Watkins Glen, New York

Specimen I.D.	Depth Interval (feet)	Specimen Length (inches)	Specimen Diameter (inches)
Length-to-Diameter — L:D = [redacted]			
WG/59/35/1-1	[redacted]	[redacted]	[redacted]
WG/59/35/2-1/1	[redacted]	[redacted]	[redacted]
WG/59/35/3-1	[redacted]	[redacted]	[redacted]
WG/59/52/5-1	[redacted]	[redacted]	[redacted]
WG/59/52/6-1	[redacted]	[redacted]	[redacted]
WG/59/52/7-1/1	[redacted]	[redacted]	[redacted]
Length-to-Diameter — L:D = [redacted]			
WG/59/35/2-1/2	[redacted]	[redacted]	[redacted]
WG/59/36/2-1/2	[redacted]	[redacted]	[redacted]
WG/59/36/2-1/3	[redacted]	[redacted]	[redacted]
WG/59/36/3-1/2	[redacted]	[redacted]	[redacted]
WG/59/36/3-1/3	[redacted]	[redacted]	[redacted]
WG/59/44/2-1/2	[redacted]	[redacted]	[redacted]
WG/59/44/2-1/3	[redacted]	[redacted]	[redacted]
WG/59/45/1-1/2	[redacted]	[redacted]	[redacted]
WG/59/45/1-1/3	[redacted]	[redacted]	[redacted]
WG/59/52/4-1/2	[redacted]	[redacted]	[redacted]
WG/59/52/4-1/3	[redacted]	[redacted]	[redacted]

2.2.3 Specimen Identification Numbers

All of the finished test specimens identified in Tables 2-1 and 2-2 were given unique specimen identification numbers. A typical specimen identification number is:

WG/59/4/1

where:

WG = Watkins Glen, New York
59 = Well No. 59

4	=	Piece number
1	=	RE/SPEC identification number.

The piece numbers given in the specimen identification numbers are identical to those used by Vogt and Foster [1995] and Vogt [1995]. The RE/SPEC identification number indicates relative depth within a given piece of rock. In the typical specimen identification number given above, the number "1" indicates the specimen was taken from the top of piece number "4."

3.0 TEST PROCEDURES

Three types of mechanical properties tests were performed on the salt recovered from Well No. 58 and Well No. 59. The tests included (1) Brazilian indirect tension tests, (2) confined quasi-static compression tests performed under conditions of CMS, and (3) confined creep tests. Two types of tests were performed on the [redacted] recovered from Well No. 59 and included (1) Brazilian indirect tension tests, and (2) confined quasi-static compression tests performed under conditions of STC. All the mechanical properties testing was performed by RE/SPEC Inc. personnel in our laboratory facilities in Rapid City, South Dakota. The testing of salt from Well No. 58 was performed during July 1995 through September 1995, while the testing of salt and [redacted] from Well No. 59 was performed during November and December 1995.

Each of the types of tests identified above is a standard test performed at RE/SPEC. As such, the tests are conducted according to documented test procedures which include:

> **Test Procedure TP-03**, RSI Standard Procedure for *Jacketing of Solid Cylindrical Specimens for Triaxial Testing, Rev. 3.*
>
> **Test Procedure TP-04a**, RSI Standard Procedure for *Direct and Indirect (Brazilian) Tension Tests, Rev. 1.*
>
> **Test Procedure TP-04b**, RSI Standard Procedure for *Triaxial Compression Creep Tests, Rev. 4.*
>
> **Test Procedure TP-04g**, RSI Standard Procedure for *Triaxial Compression Constant Axial or Lateral Strain Rate Tests Using the Universal Test System, Rev. 1.*
>
> **Test Procedure TP-05**, RSI Standard Procedure for *Data Handling and Storage, Rev. 3.*

The confined quasi-static compression tests at constant mean stress are a variation of Test Procedure TP-04g in which the specimen is first hydrostatically loaded to a specified confining pressure or mean stress, and then the confining pressure is decreased while the axial stress is simultaneously increased at a rate to maintain the mean stress (i.e., the average of the three principal stresses) constant at the specified value.

The testing requires use of sophisticated, computer-controlled test systems equipped with electronic transducers used to measure force, pressure, displacement, and temperature. The transducers are calibrated at regular intervals using in-house standards that have been certified by the National Institute of Standards and Technology (NIST). Calibrations are performed by RE/SPEC personnel using standard documented procedures. The calibration procedures specifically required in the testing include:

Calibration Procedure CP-02, RSI Standard Procedure for *Calibration and Verification of Pressure Measuring Systems, Rev. 2.*

Calibration Procedure CP-03, RSI Standard Procedure for *Calibration and Verification of Load Measuring Systems in Testing Machines, Rev. 5.*

Calibration Procedure CP-04, RSI Standard Procedure for *Calibration and Verification of Deformation Measuring Systems, Rev. 3.*

Calibration Procedure CP-08, RSI Standard Procedure for *Calibration and Verification of Temperature Measuring Systems, Rev. 1.*

Calibration Procedure CP-09, RSI Standard Procedure for *Calibration and Verification of Liquid Volume Displacement Measuring Systems, Rev. 2.*

The testing systems including the electronics are housed in an environmentally controlled facility in which the temperatures are maintained at 20 ± 1°C (68 ± 2°F).

4.0 MECHANICAL PROPERTIES TEST RESULTS FOR [redacted]

Two types of mechanical properties tests were performed on the [redacted] recovered from Well No. 59; i.e.:

- Brazilian indirect tension tests.
- Confined quasi-static compression tests.

The results of these tests are summarized below.

4.1 BRAZILIAN INDIRECT TENSION TESTS

Apparent tensile strengths of the [redacted] from Well No. 59 were determined by means of the indirect tension test, commonly termed the Brazilian indirect tension test. This method is termed an indirect method because a compressive, diametral line load is applied over the length of a cylindrical specimen having a length-to-diameter ratio 0.5. The compressive load induces a tensile stress at the center of the specimen perpendicular to the diametral line load. As the compressive line load increases, so does the tensile stress. The tensile strength is computed according to:

$$T_o = \frac{2P}{\pi DL} \tag{4-1}$$

where:

T_o	=	apparent tensile strength, psi
P	=	line load at failure, lbs
D	=	specimen diameter, inches
L	=	specimen length, inches.

Eleven indirect tension tests were performed on the [redacted] taken from Well No. 59 at depths ranging from [redacted] All tests were performed at a temperature of [redacted] The results of the tests are summarized in Table 4-1. As shown, the tensile strengths are quite [redacted] ranging from a [redacted] with a mean and standard deviation of [redacted] and [redacted] respectively.

4.2 CONFINED QUASI-STATIC COMPRESSION TESTS

Three quasi-static compression tests were performed on the [redacted] recovered from each of two depths within Well No. 59 for a total of six tests. The depth intervals were [redacted] and [redacted], respectively. The tests were performed with constant confining pressure in a test configuration commonly referred to as a standard triaxial compression (STC) test. Three nominal confining pressures were imposed during the tests; i.e.; [redacted] All tests were conducted by increasing the axial load in axial strain control at a rate of [redacted] until the specimen failed. The temperature in the tests was [redacted]. The data obtained from the tests were used to determine compressive strength and two elastic moduli; i.e., Young's modulus and Poisson's ratio. The compressive strength is a measure of how much load the rock can carry at a specified confining pressure and the elastic moduli define the level of elastic deformation the rock undergoes during loading.

Table 4-1. Summary of Results From Indirect Tension Tests on [redacted] From Well No. 59, Seneca Lake Storage Project, Watkins Glen, New York

Specimen I.D.	Apparent Tensile Strength (psi)
WG/59/35/2-1/2	[redacted]
WG/59/36/2-1/2	[redacted]
WG/59/36/2-1/3	[redacted]
WG/59/36/3-1/2	[redacted]
WG/59/36/3-1/3	[redacted]
WG/59/44/2-1/2	[redacted]
WG/59/44/2-1/3	[redacted]
WG/59/45/1-1/2	[redacted]
WG/59/45/1-1/3	[redacted]
WG/59/52/4-1/2	[redacted]
WG/59/52/4-1/3	[redacted]
Mean **Standard Deviation**	[redacted]

During each test, measurements of axial force, confining pressure (σ_3) and axial and radial displacement were made with electronic transducers. Axial stress, σ_1, was calculated from the axial force and the current cross-sectional area of the specimen. Axial and radial true strains (ε_1 and ε_3) were calculated from the specimen dimensions and the axial and radial displacements, respectively. The data acquired from each test were also used to calculate the axial stress difference; i.e., the difference between the axial stress and the confining pressure or $\Delta\sigma_1$

$= \sigma_1 - \sigma_3$. The stress difference is plotted as a function of axial and radial strain for all the tests in Appendix A and a typical stress-strain plot is shown in Figure 4-1.

As shown in the typical stress-strain plot in Figure 4-1, [redacted] response between stress difference and strain from initial loading through failure. Failure is denoted by a peak in the stress difference-versus-strain curves followed by a sharp drop in stress difference with accumulating strains. The failure or peak stress difference is known as the quasi-static compressive strength and is the ultimate load the rock can carry for the prescribed confining pressure. The quasi-static compressive strength (or peak stress difference) measured in each test is summarized in Table 4-2. In all cases, the strains corresponding to failure are [redacted]

Table 4-2. Summary of Results From Confined Quasi-Static Compression Tests on [redacted] From Well No. 59, Seneca Lake Storage Project, Watkins Glen, New York

Specimen I.D.[a]	Average Confining Pressure (psi)	Peak Axial Stress Difference, $\Delta\sigma_1$ (psi)	$\sqrt{J_2}$ (psi)	I_1 (psi)	Elastic Moduli	
					Young's Modulus, E	Poisson's Ratio, ν
WG/59/35/1-1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/35/2-1/1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/35/3-1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/52/7-1/1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/52/5-1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/52/6-1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

(a) Piece 35 covers a depth interval from [redacted] Piece 52 covers a depth interval from [redacted]

The quasi-static compressive strengths shown in Table 4-2 indicate, in general, that the [redacted] This result is typical of materials such as rocks and soils. A common method of illustrating this behavior is to plot the strength data in the $\sqrt{J_2}$-versus-I_1 stress space where J_2 is the second invariant of the deviator stress tensor and I_1 is the first invariant of the stress tensor. These two invariants are measures of shear stress and mean stress (or confining pressure), respectively, and are defined as:

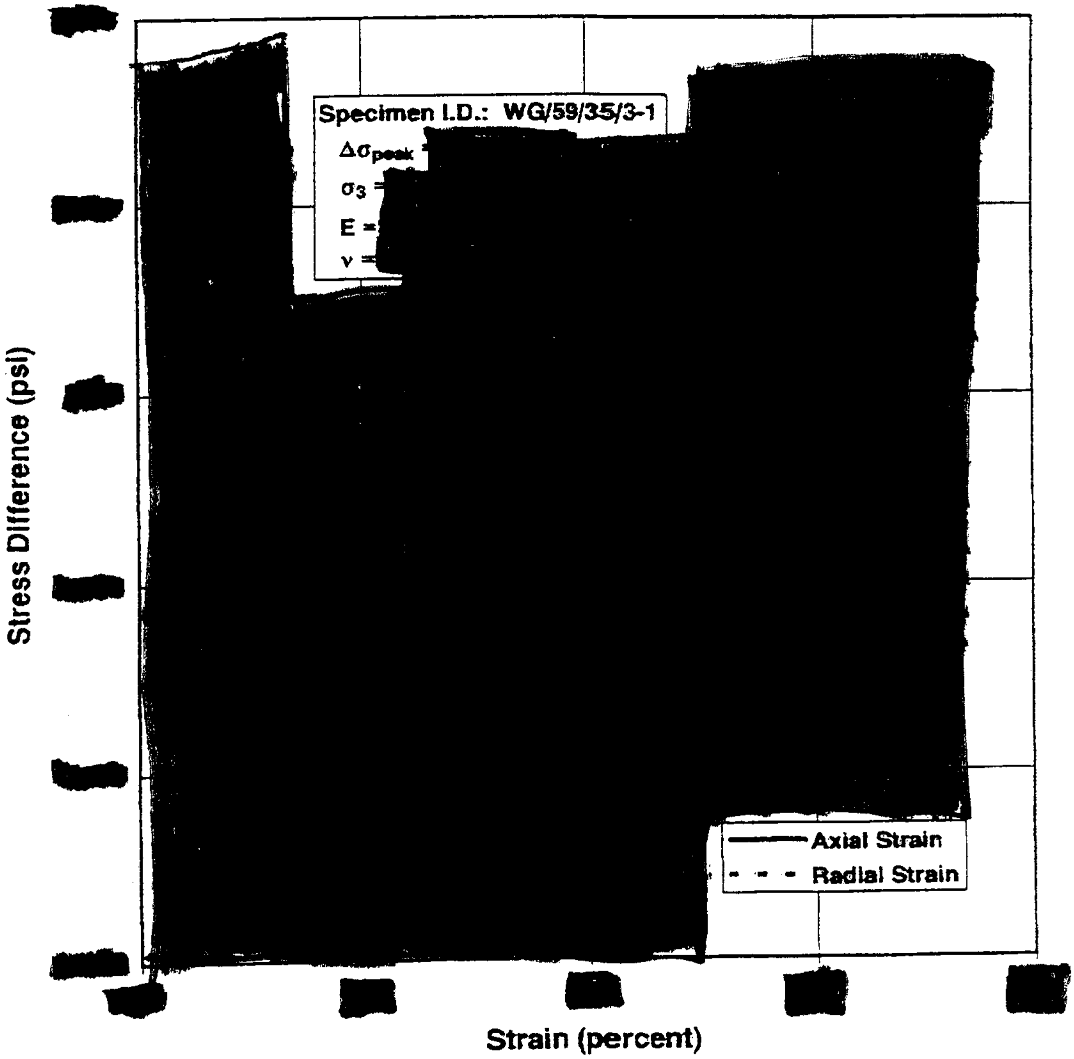

Figure 4-1. Axial Stress Difference Versus Strain for a Typical Confined Quasi-Static Compression Test on [redacted] From Well No. 59.

$$\sqrt{J_2} = \frac{\Delta\sigma_1}{\sqrt{3}} \tag{4-2}$$

$$I_1 = \Delta\sigma_1 + 3\sigma_3$$

where $\Delta\sigma_1$ is the failure or peak stress difference and σ_3 is the confining pressure. The failure stress for each of the six quasi-static compression tests in terms of these two invariants are given in Table 4-2 and plotted in Figure 4-2. As shown in Figure 4-2, $\sqrt{J_2}$ is approximately linearly related to I_1. If a straight line is fitted to the data, the relationship between $\sqrt{J_2}$ and I_1 can be expressed as follows:

[redacted] (4-3)

This linear relationship is plotted in Figure 4-2 to show how well it fits the data. The relationship between $\sqrt{J_2}$ and I_1 for the [redacted] divides the stress space into domains of stress that do not fail the [redacted] and stress states that result in failure. For stress states below the $\sqrt{J_2}$-versus-I_1 curve, failure is not expected. Above the curve, failure will occur.

The elastic moduli, Young's modulus, E, and Poisson's ratio, ν, describe how a material such as rock deforms elastically. Elastic deformation is the deformation that is recovered when a material is unloaded much like a spring recovers its normal shape after it is unloaded. Young's modulus is a measure of the change in axial stress per unit change in axial strain while Poisson's ratio is a measure of the change in radial strain per unit change in axial strain. In this study, the elastic moduli were determined from:

$$E = \frac{\Delta\sigma_1}{\Delta\varepsilon_1} \tag{4-4}$$

$$\nu = -\frac{E}{\dfrac{\Delta\sigma_1}{\Delta\varepsilon_3}} \tag{4-5}$$

where $\Delta\sigma_1$ is the change in axial stress and $\Delta\varepsilon_1$ and $\Delta\varepsilon_3$ are the changes in the axial and radial strains, respectively. Equation 4-4 and the denominator of Equation 4-5 represent the slopes of the axial stress difference versus axial strain and axial stress difference versus radial strain curves, respectively. Equations 4-4 and 4-5 were used to calculate the elastic moduli for a region of the stress-strain curves given in Appendix A bounded by [redacted] of the peak stress difference. The moduli determined from each test are summarized in Table 4-2. Young's modulus varies from [redacted] Poisson's ratio varies from [redacted] Unload/reload cycles (often used for salt rocks) were not performed during the tests because it was assumed that the elastic properties determined from the initial loading curves would be similar to those determined from unload/reload data [redacted]ck.

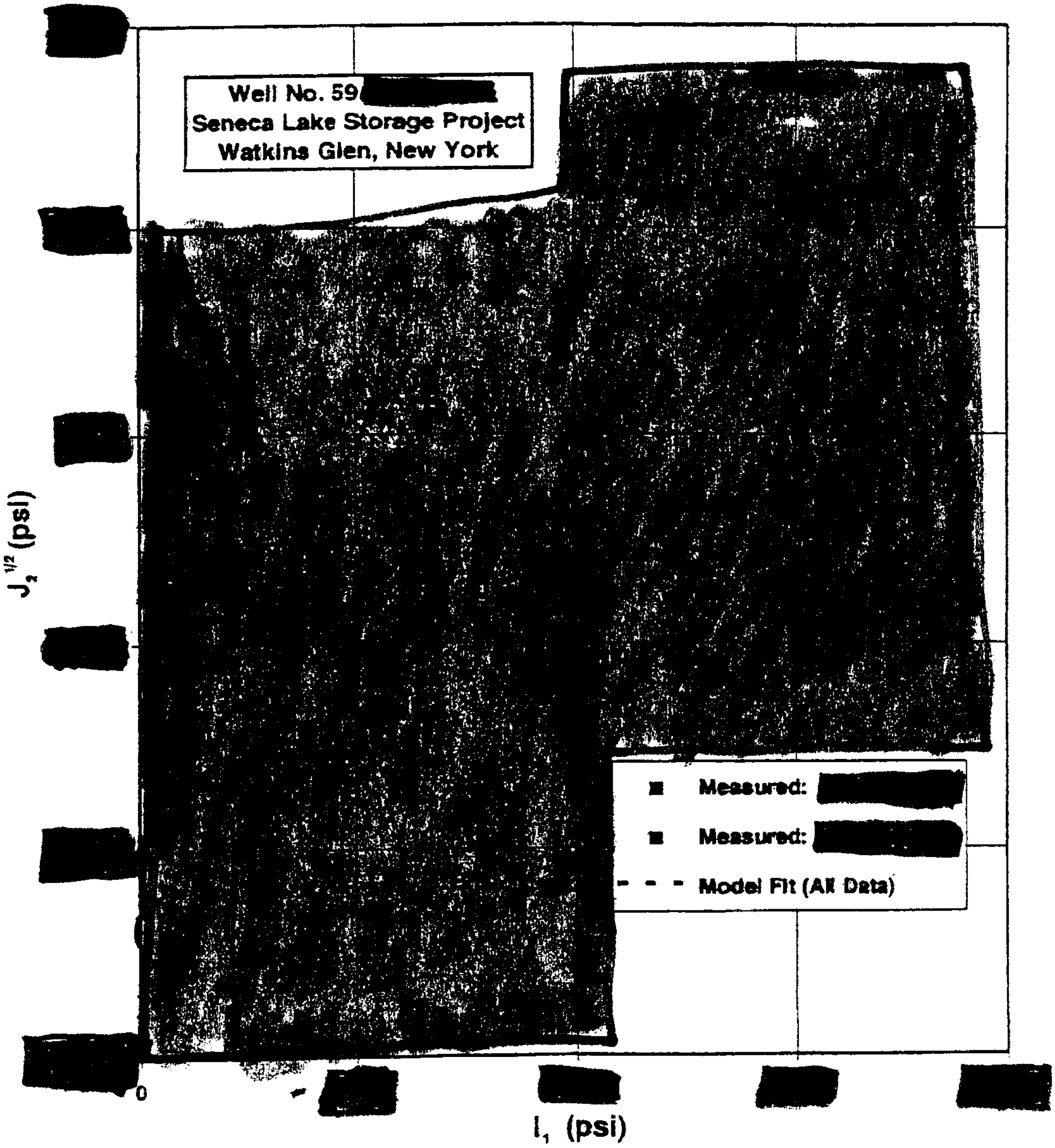

Figure 4-2. $\sqrt{J_2}$ Versus I_1 From Strength Testing of [redacted] From Well No. 59.

5.0 MECHANICAL PROPERTIES TEST RESULTS FOR SALT

Three types of mechanical properties tests were performed on the Well No. 58 and Well No. 59 salt; i.e.:

- Brazilian indirect tension tests.
- Confined quasi-static compression tests performed at a constant mean stress.
- Confined creep tests.

The results of these tests are summarized below.

5.1 BRAZILIAN INDIRECT TENSION TESTS

Apparent tensile strengths of the Well No. 58 and Well No. 59 salt were determined by means of the Brazilian indirect tension test (see description in Section 4.1). Five tests were performed on specimens of Well No. 58 salt and six tests were performed on Well No. 59 salt for a total of eleven tests. The temperature in all tests was [redacted] and the tensile strengths were calculated from Equation 4-1.

The results of the Brazilian indirect tension tests are summarized in Table 5-1. As shown, the tensile strengths of the Well No. 59 specimens are, on average, [redacted]. The mean strengths for the Well No. 58 and Well No. 59 salt are [redacted] respectively while the corresponding standard deviations were [redacted] respectively. As indicated by the standard deviations, the variability in the tensile strength of the Well No. 59 salt is [redacted] Figure 5-1 provides a comparison between the mean apparent tensile strengths of the Well No. 58 and Well No. 59 salt and several other bedded and domal salts. As shown, the tensile strengths are [redacted]

5.2 CONFINED QUASI-STATIC COMPRESSION TESTS

A total of six confined quasi-static compression tests were performed on the salt from Well No. 58 and Well No. 59. All tests were performed in a CMS test configuration in which the axial stress, σ_1, is increased and the confining pressure, σ_3, is simultaneously decreased at rates which produce no change in the mean stress, σ_m, imposed on the specimen. The primary objective of these types of tests was to determine the dilational characteristics (volume expansion caused by microfracturing) of the salt. These dilational characteristics are discussed separately in Section 5.4.

Table 5-1. Summary of Results From Indirect Tension Tests on Well No. 58 and Well No. 59 Salts, Seneca Lake Storage Project, Watkins Glen, New York

Well No. 58 Salt		Well No. 59 Salt	
Specimen I.D.	**Tensile Strength (psi)**	**Specimen I.D.**	**Tensile Strength (psi)**
WG/58/1/2	[redacted]	WG/59/78/3/1	[redacted]
WG/58/4/2	[redacted]	WG/59/78/3/2	[redacted]
WG/58/6/3	[redacted]	WG/59/78/3/3	[redacted]
WG/58/8/3	[redacted]	WG/59/78/3/4	[redacted]
WG/58/8/4	[redacted]	WG/59/78/5/2	[redacted]
		WG/59/78/5/3	[redacted]
Mean Standard Deviation	[redacted]	**Mean Standard Deviation**	[redacted]

In the constant mean stress test, the test specimen is first loaded hydrostatically by applying radial stress (or confining pressure), σ_3, and axial stress, σ_1, in equal increments until the mean stress specified for the test has been reached. Then a shear stress is applied by increasing the axial stress and simultaneously decreasing the radial stress. During shearing, the axial stress rate is twice the radial stress rate (with opposite algebraic sign) to maintain a state of constant mean stress. Tests are terminated either when the specimen fails or when the confining pressure has been completely removed (i.e., tensile radial stresses cannot be induced in the test specimen with this test configuration). In these tests, the confining pressure reached zero before the specimen failed in all cases.

Three CMS tests each were performed on Well No. 58 and Well No. 59 salt specimens at a temperature of [redacted] The nominal mean stress levels used in the Well No. 58 tests were [redacted] while the nominal mean stress levels used in the Well No. 59 tests were [redacted] A stress difference-versus-strain plot for a typical CMS test is shown in Figure 5-2 and the stress-strain plots for all the CMS tests are given in Appendix B. Because the mean stress is not changing during the CMS tests, the volumetric strains [redacted] This behavior is consistent with a material that is [redacted] However, at some elevated stress difference level [redacted] the volumetric strain rate [redacted] The stress levels at which [redacted] in the CMS tests (i.e., the stress at which the [redacted] are summarized in Table 5-2.

Figure 5-1. Comparison of Apparent Tensile Strengths of Well No. 58 and Well No. 59 Salt With Other Salts.

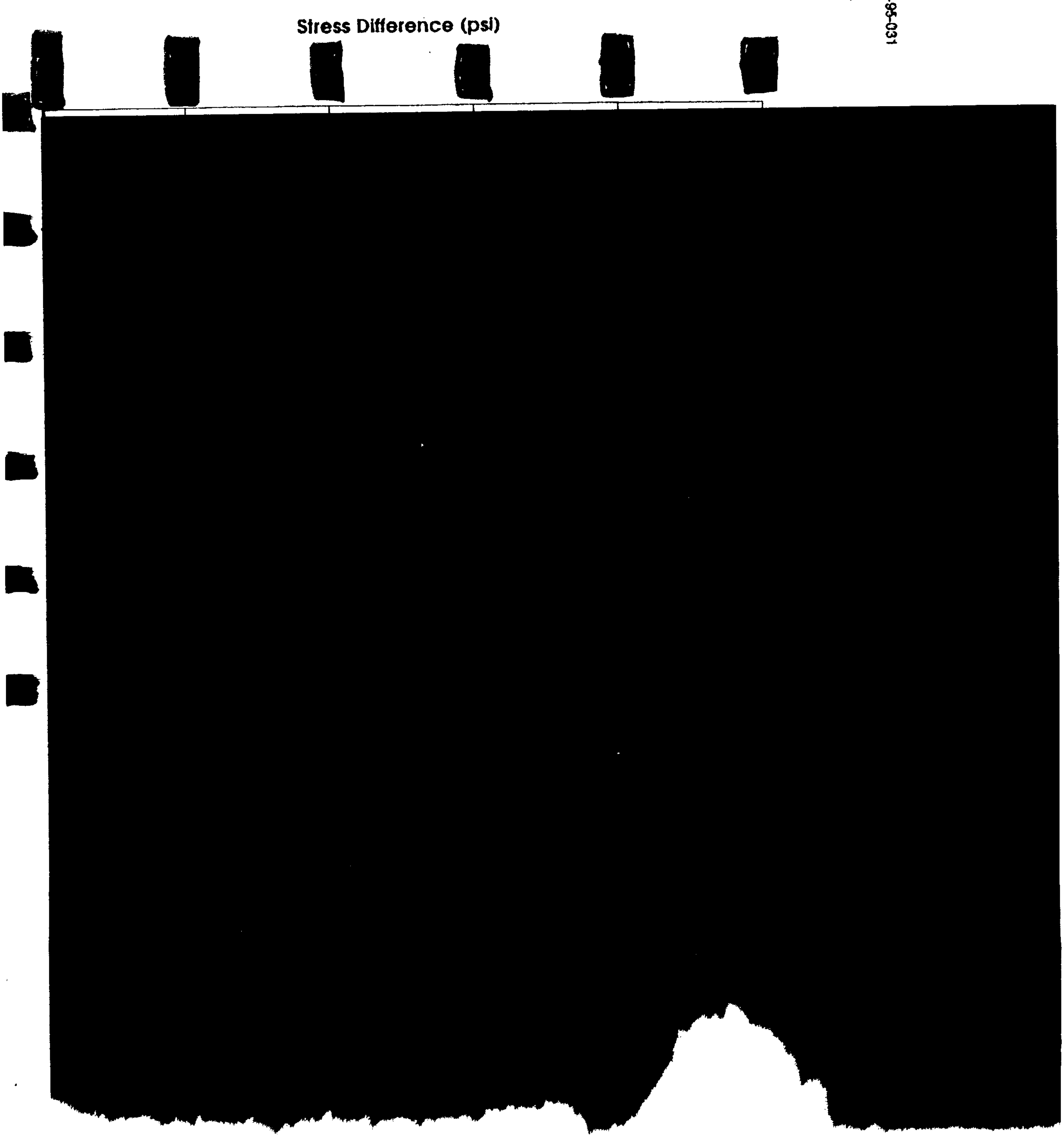

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Table 5-2. Summary of Results From Constant Mean Stress Tests on Well No. 58 and Well No. 59 Salts, Seneca Lake Storage Project, Watkins Glen, New York

Specimen I.D	Average Mean Stress (psi)	Stress State at Dilation		
		Axial Stress, σ_1 (psi)	Radial Stress, σ_3 (psi)	Axial Stress Difference, $\Delta\sigma_1$ (psi)
Well No. 58 Salt				
WG/58/4/1	[redacted]	[redacted]	[redacted]	[redacted]
WG/58/6/1	[redacted]	[redacted]	[redacted]	[redacted]
WG/58/6/2	[redacted]	[redacted]	[redacted]	[redacted]
Well No. 59 Salt				
WG/59/78/2	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/77/4	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/78/7	[redacted]	[redacted]	[redacted]	[redacted]

(a) Poor volumetric strain measurement. No dilation stress state determined.

5.3 CONFINED CREEP TESTS

Three confined creep tests each were performed on salt from Well No. 58 and Well No. 59 for a total of six tests. The tests were performed primarily to evaluate the time-dependent behavior of the salt. However, data were also acquired to further characterize the dilational characteristics of the salt and to estimate two elastic properties, Young's Modulus, E, and Poisson's ratio, ν.

Each of the six creep tests comprised three separate stages in which the temperature, confining pressure (or radial stress), and the stress difference (axial stress minus radial stress) were held constant for the duration of the stage. The stress conditions for the tests are given in the test matrix shown in Table 5-3. The first stage of each test was performed at a temperature of [redacted] a confining pressure of [redacted] psi, and a stress difference of either [redacted] The stress differences were selected to encompass the range of stress differences expected to exist in the salt surrounding the proposed cavern, while the confining pressure was selected to simulate the lithostatic stress in the salt at the cavern midheight. The confining pressure in the first stage was [redacted] In subsequent stages of each test, the confining pressure was lowered while the stress difference and temperature were maintained at the levels established for the first stage. This loading sequence was designed to simulate drawdown of the cavern pressure and to acquire data from which dilational characteristics of the salt could be examined. At the end of each stage, the stress difference was removed before the confining pressure was changed to ensure that no creep strain accumulated between stages. The data acquired while the stress difference was removed were used to estimate the two elastic properties. The duration of each multistage creep test was approximately [redacted]

Table 5-3. Creep Test Matrix for Well No. 58 and Well No. 59 Salt Cores, Seneca Lake Storage Project, Watkins Glen, New York

Specimen I.D.	Stage[a]	Confining Pressure (psi)	Axial Stress (psi)	Stress Difference (psi)	Duration [redacted]
WG/58/7/1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/58/7/3	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/58/7/2	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/77/2	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/77/3	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/78/1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

(a) Temperature during each stage was [redacted]
(b) Dilation observed during the stage.

To initiate each creep test, the confining pressure was applied to all exterior surfaces of a salt specimen (jacketed in a flexible membrane to protect it from the pressurizing medium) and then heated to the prescribed temperature of [redacted] Once the confining pressure and temperature stabilized, axial stress was quickly applied to the ends of the specimen until the target stress difference was reached, at which time the confining pressure and stress difference were maintained at their specified levels for the duration of the stage. When the first stage ended, the stress difference was removed by lowering the axial stress down to the confining pressure. In subsequent stages of each test, the confining pressure was lowered and permitted to stabilize at the new target level. Then the axial stress difference was reapplied, and the confining pressure and axial stress difference were maintained for the duration of the stage.

During the test, axial force, confining pressure, axial displacement, radial displacement, and temperature were recorded. Axial stress was calculated from the axial force and the current cross-sectional area of the specimen. Axial and radial true (logarithmic) strains were calculated from the axial and radial displacements and the specimen dimensions.

The axial, radial, and volumetric creep strains for a typical test on the salt from Well No. 58 and Well No. 59 are shown in Figure 5-3. The small discontinuities in the strain-time curves at [redacted] denote the times at which the confining pressure was changed from one stage to the next. The Stage 1 portions of the curves are [redacted], while [redacted]. At early times, the [redacted] In contrast, the at later times, the [redacted] volumetric strain during the first stage [redacted] indicating a [redacted] During Stage 2, the [redacted] In the third stage of this test, the [redacted] This [redacted] is termed [redacted] and the stress states that produce the [redacted] It should be noted that [redacted] could occur in any of the stages of a creep test depending on the imposed stress conditions; however, in this study, the stress states imposed during the first stages of each test were selected to [redacted] during the stage. In subsequent stages, the confining pressure was successively [redacted] to determine the stress state(s) at which [redacted] Table 5-3 denotes those stages and stress states that [redacted] in the creep tests performed on Well No. 58 and Well No. 59 salt. Additional discussion of [redacted] is presented in Section 5.4. The creep histories for each of the six creep tests are given in Appendix C.

The axial strains for each of the six creep tests performed on Well No. 58 and Well No. 59 salt are shown in Figure 5-4. As shown, the strains are strongly influenced [redacted] by the imposed stress difference with [redacted] corresponding to [redacted] This result is [redacted]. Figure 5-4 also shows that the creep strains measured in the tests on Well No. 58 salt are comparable to those measured in the tests on Well No. 59 salt. At the higher stress differences (i.e., stress differences of [redacted] the creep strains for Well No. 59 salt are [redacted] the creep strains for Well No. 58 salt; however at the [redacted], the trend is [redacted]

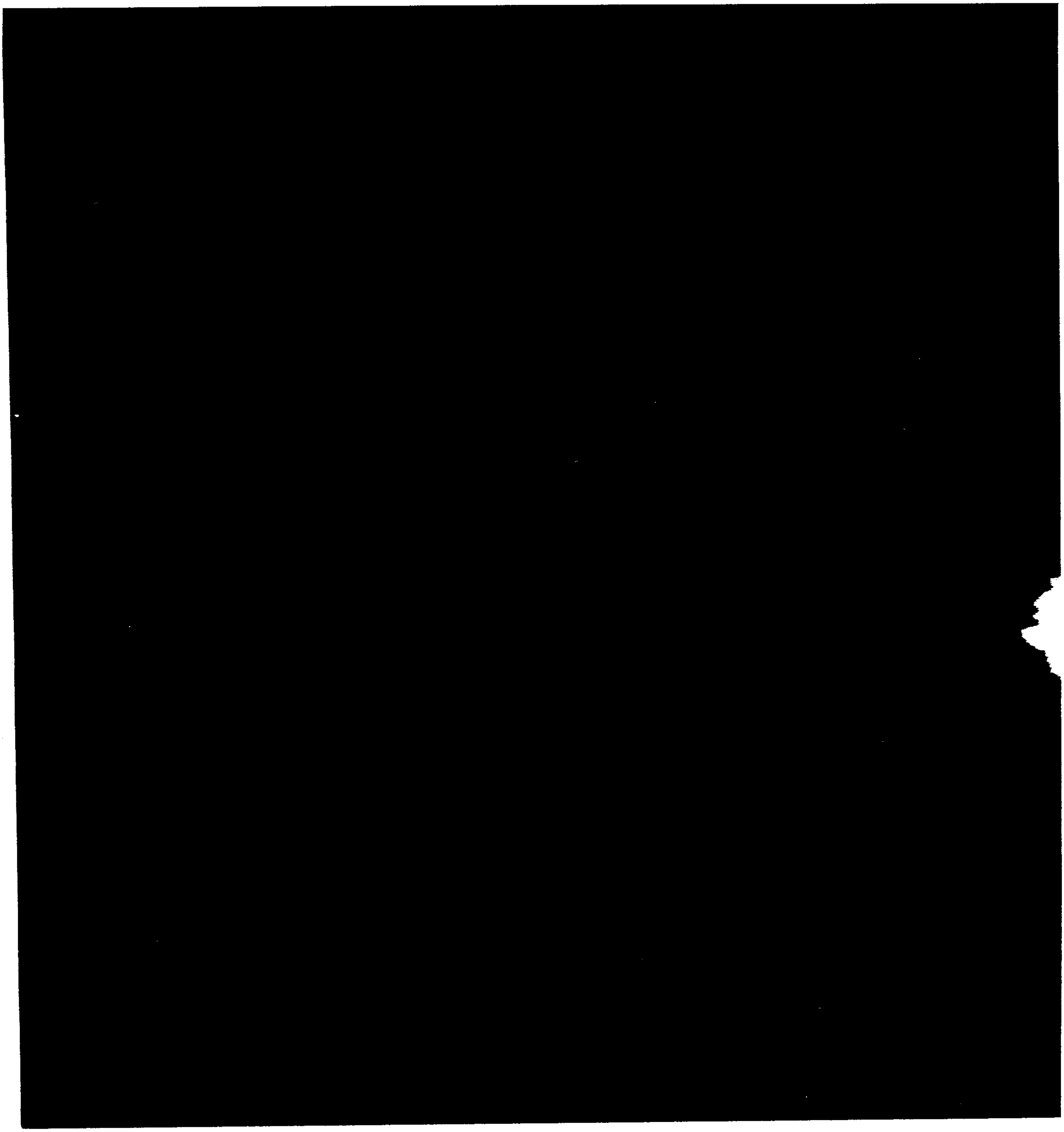

Figure 5-3. Axial, Radial, and Volumetric Creep Strains for a Typical Creep Test on Salt, Seneca Lake Storage Project, Watkins Glen, New York.

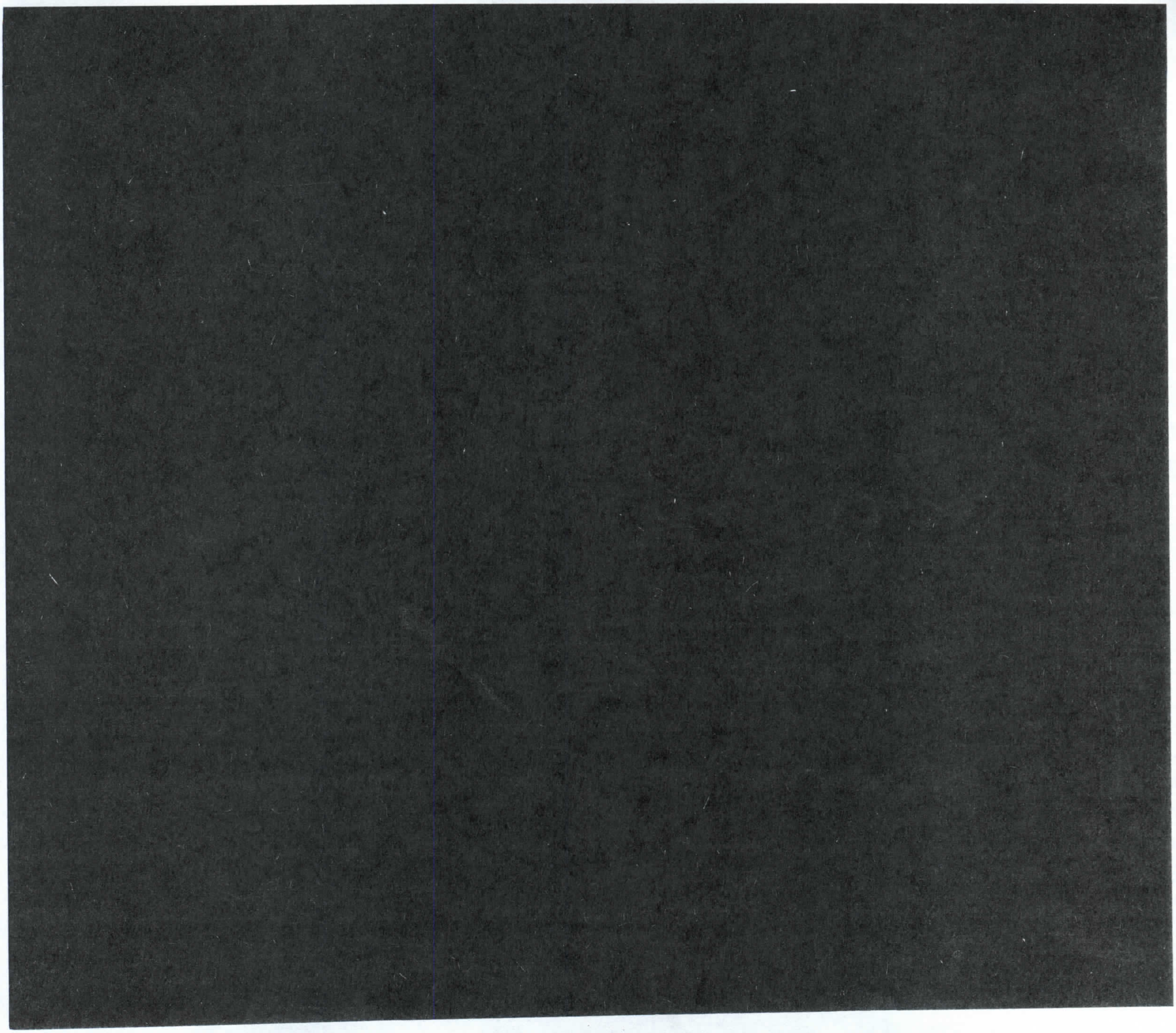

Figure 5-4 Comparison of Axial Creep Strains for Well No. 58 and Well No. 59 Salts at Stress Differences of [redacted], Seneca Lake Storage Project, Watkins Glen, New York.

5.4 DILATIONAL CHARACTERISTICS

The stress difference ($\sigma_1 - \sigma_3$) at which dilation occurs either in a confined quasi-static compression test or confined creep test is referred to as the dilational stress limit. The magnitude of this stress depends on the magnitude of the mean stress (or confining pressure). Ratigan et al. [1991] have proposed a linear relationship for the dilational stress limit using the results of tests performed on Avery Island domal salt and southeastern New Mexico bedded salt. This relationship can be expressed as follows:

$$\sqrt{J_2} = 0.27\ I_1 \qquad (5\text{-}1)$$

where J_2 is the second invariant of the deviator stress tensor and I_1 is the first invariant of the Cauchy stress tensor. J_2 and I_1 can be related to the stress difference and mean stress in a quasi-static compression test or creep test through the following relationships:

$$\sqrt{J_2} = \frac{\sigma_1 - \sigma_3}{\sqrt{3}} = \frac{\Delta\sigma_1}{\sqrt{3}} \qquad (5\text{-}2)$$

$$I_1 = 3\,\sigma_m = \left(\sigma_1 + 2\,\sigma_3\right) = \Delta\sigma_1 + 3\sigma_3 \qquad (5\text{-}3)$$

where σ_m is the mean stress and the $\Delta\sigma_1$, is the stress difference.

The dilational stress states determined from the confined quasi-static compression tests on Well No. 58 and Well No. 59 salt are shown in Figure 5-5 and tabulated in Table 5-4. Also shown in Figure 5-5 are both the nondilating and dilating stress states determined from the confined creep tests and the dilational stress limit proposed by Ratigan et al. [1991]. As shown, the dilational stress states for the Well No. 58 and Well No. 59 salt determined from both the quasi-static compression and confined creep tests are [redacted]

[redacted]

Recall, the dilation limit is the condition for which the volumetric strain rate of the specimen changes from zero to some extremely small negative number. [redacted]

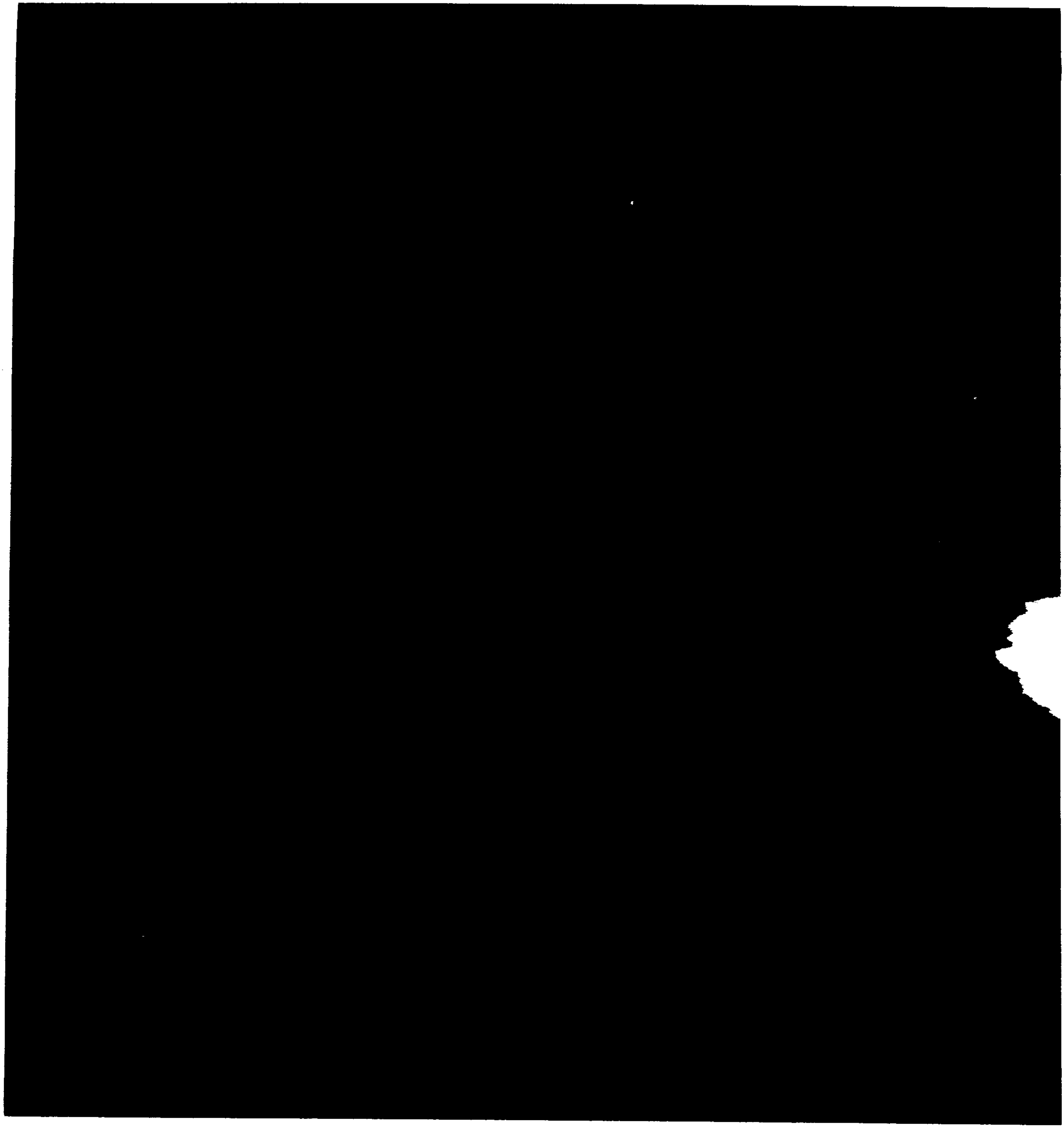

Figure 5-5. Dilation Stress States for Well No. 58 and Well No. 59 Salts, Seneca Lake Storage Project, Watkins Glen, New York.

Table 5-4. Summary of Dilation Stress States for Well No. 58 and Well No. 59 Salt, Seneca Lake Storage Project, Watkins Glen, New York

Specimen I.D.	Axial Stress, σ_1 (psi)	Radial Stress, σ_3 (psi)	Stress Difference, $\Delta\sigma_1$ (psi)	I_1 (psi)	$\sqrt{J_2}$ (psi)
	[redacted]				
WG/58/4/1[a]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/58/6/1[a]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/58/6/2[a]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/78/2[a]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/78/7[a]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/58/7/3	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/58/7/2	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/78/1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]				
WG/58/7/1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/58/7/3	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/58/7/2	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/77/2	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/77/3	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
WG/59/78/1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

(a) Confined quasi-static compression test performed under conditions of constant mean stress.

[redacted] It should be noted that the test performed on the [redacted]

If the [redacted], then the dilation limit line in Figure 5-5 [redacted]. The region above the limiting line represents stress states that will produce dilation, while the region below the line represents stress states in which no dilation occurs. If a stress state determined from a geomechanical structural analysis is in the nondilating region, then it can be assumed that the salt subjected to this stress will not dilate and stability is reasonably assured. However, if a stress state lies in the dilating region, then the salt subjected to this stress is expected to dilate, a condition detrimental to the stability of the structure. A geomechanical analysis (including a comparison of predicted stress states to the dilational stress states represented in Figure 5-5) is presented by Osnes and Eyermann [1996].

5.5 ELASTIC PROPERTIES

At the conclusion of each stage of the confined creep tests described in Section 5.3, the stress difference was removed before the confining pressure was lowered for the subsequent stage. During this unloading process, [redacted] These [redacted] are predominantly [redacted] and can be used to determine two elastic properties; i.e., Young's modulus, E, and Poisson's ratio, ν. Using Equations 4-4 and 4-5, the elastic properties for Well No. 58 and Well No. 59 salt were determined and are summarized in Table 5-5. The mean values for Young's modulus and Poisson's ratio were [redacted] respectively. Both of these values are [redacted]

Table 5-5 Summary of Elastic Properties for Well No. 58 and Well No. 59 Salt, Seneca Lake Storage Project, Watkins Glen, New York

Specimen I.D.	Stage	Elastic Properties: Young's Modulus, E [redacted]	Elastic Properties: Poisson's Ratio, ν
WG/58/7/2	1	[redacted]	[redacted]
WG/59/77/3	2	[redacted]	[redacted]
WG/59/78/1	1	[redacted]	[redacted]
	2	[redacted]	[redacted]
Mean Standard Deviation		[redacted]	[redacted]

6.0 SUMMARY AND CONCLUSIONS

New York State Electric & Gas Corporation (NYSEG) is developing its Seneca Lake Storage Project near Watkins Glen, New York, to improve natural gas supply options for central New York. The project includes converting an existing solution-mined cavern owned by Akzo Nobel Salt to compressed natural gas storage service. The cavern, developed in the bedded salts of New York State, was previously used for brine production and later for liquefied petroleum gas (LPG) storage service. RE/SPEC Inc. performed mechanical properties testing on salt cores from Well No. 58 and Well No. 59 and on nonsalt [redacted] cores from Well No. 59. The testing comprised:

- Brazilian indirect tension tests on salt cores recovered from Well No. 58 and Well No. 59 and on [redacted] core recovered from Well No. 59.
- Confined quasi-static compression tests on salt cores recovered from Well No. 58 and Well No. 59 and on [redacted] core recovered from Well No. 59.
- Confined creep tests on salt cores recovered from Well No. 58 and Well No. 59.

Eleven Brazilian indirect tension tests were performed on [redacted] cores recovered from Well No. 59. The results indicated that the apparent tensile strength of the [redacted] ranged from [redacted] a mean and standard deviation of [redacted] and [redacted] respectively.

Six confined quasi-static compression tests were also performed on [redacted] from Well No. 59. As expected, the compressive strength of the [redacted] increased with confining pressure. This trend was quantified mathematically using the following model:

[redacted] (6-1)

where J_2 and I_1 are the second invariant of the deviator stress tensor and the first invariant of the Cauchy stress tensor at failure, respectively. In practical terms, these two quantities represent shear stress and mean stress, respectively. The data acquired from the quasi-static tests were also used to estimate two elastic properties, Young's modulus, E, and Poisson's ratio, ν. Young's modulus is a measure of how much axial strain is recovered when a specimen is unloaded (analogous to the deformation recovered when a spring is unloaded) and ranged from [redacted] with a mean and standard deviation of [redacted] and [redacted] respectively. Poisson's ratio is a measure of how much lateral strain is recovered when a specimen is unloaded and ranged from [redacted] with a mean and standard deviation [redacted], respectively.

The apparent tensile strengths of salt specimens from Well No. 58 and Well No. 59 were also determined using the Brazilian indirect tension test. Five tests were performed on Well

No. 58 salt specimens. Tensile strengths ranged from [redacted] with a mean and standard deviation of [redacted] respectively. Six tests were performed on Well No. 59 salt specimens. The tensile strengths in these tests were, on average, [redacted] However, the range [redacted] and standard deviation [redacted] in the tensile strengths of Well No. 59 salt [redacted] The mean tensile strengths of the Well No. 58 and Well No. 59 salts are [redacted]

Six confined quasi-static compression tests were performed on salt specimens from Well No. 58 and Well No. 59. The data acquired in these tests were combined with data acquired in the multistage creep tests to assess the propensity for the salt to dilate under various stress states. The results of these tests suggest that the dilation stress states determined for the Well No. 58 and Well No. 59 salt are [redacted]

[redacted] (6-2)

The six creep tests performed on the Well No. 58 and Well No. 59 salt specimens provided data from which the time-dependent deformational characteristics of the salt could be determined. The results indicated, as expected, that the creep strains are [redacted] by the imposed stress difference with much larger strains corresponding to higher levels of stress difference. The results of the Well No. 58 creep tests were compared with those from Well No. 59 at identical test conditions and showed that the creep behavior of the salt from the two wells [redacted]

Unload data acquired at the end of several of the creep stages were used to estimate two elastic properties; i.e., Young's modulus, E, and Poisson's ratio, ν. The range in values for E and ν were [redacted] and [redacted] respectively. The mean and standard deviation for Young's modulus were [redacted] respectively; while the mean and standard deviation for Poisson's ratio were [redacted] respectively. The elastic properties determined for the Well No. 58 and Well No. 59 salt are [redacted]

7.0 REFERENCES

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APPENDIX A

STRESS-STRAIN PLOTS FOR CONFINED QUASI-STATIC COMPRESSION TESTS ON DOLOSTONE FROM WELL NO. 59

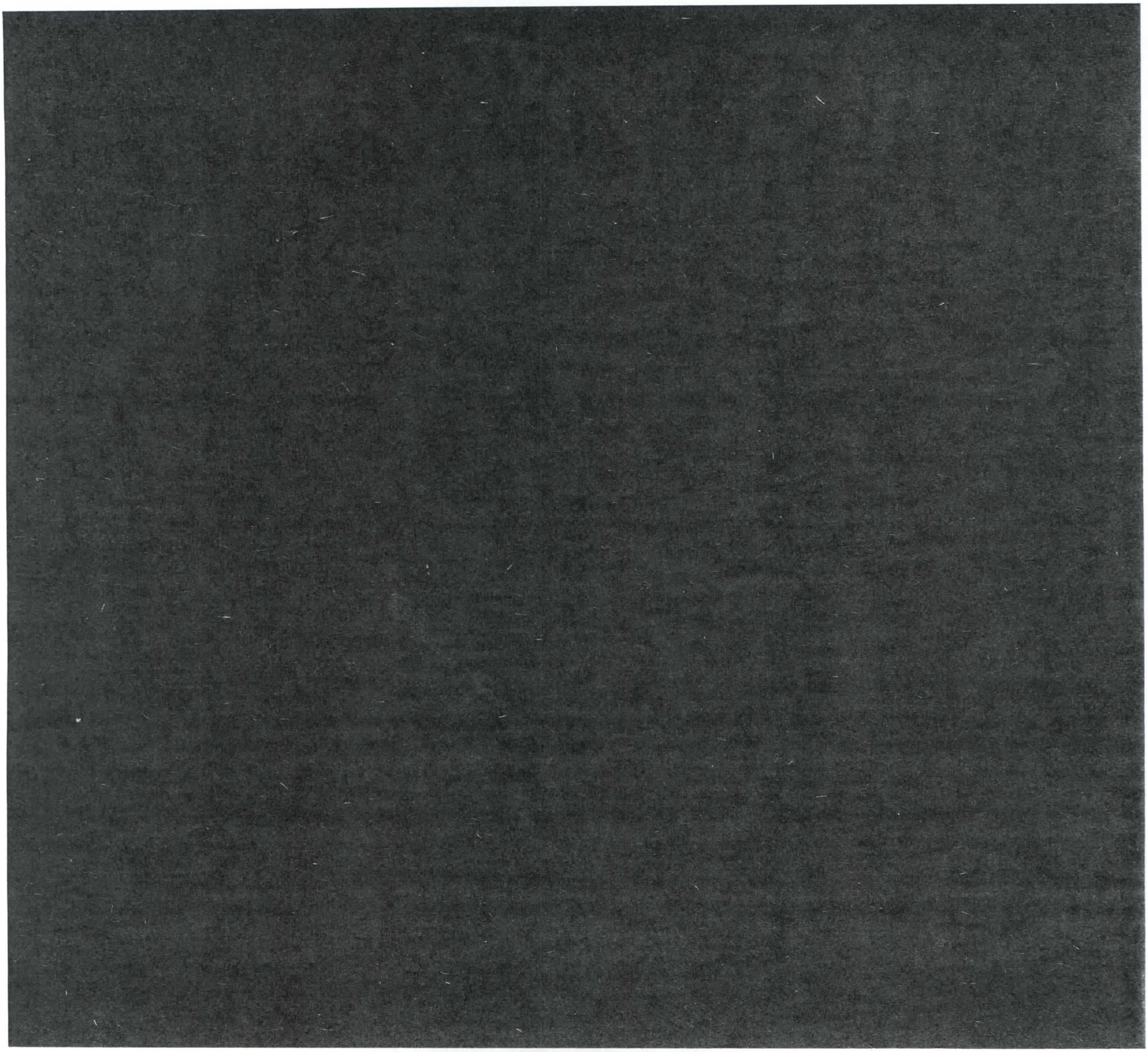

Figure A-1. Axial Stress Difference Versus Strain for [redacted] From Well No. 59 — Specimen WG/59/35/1-1.

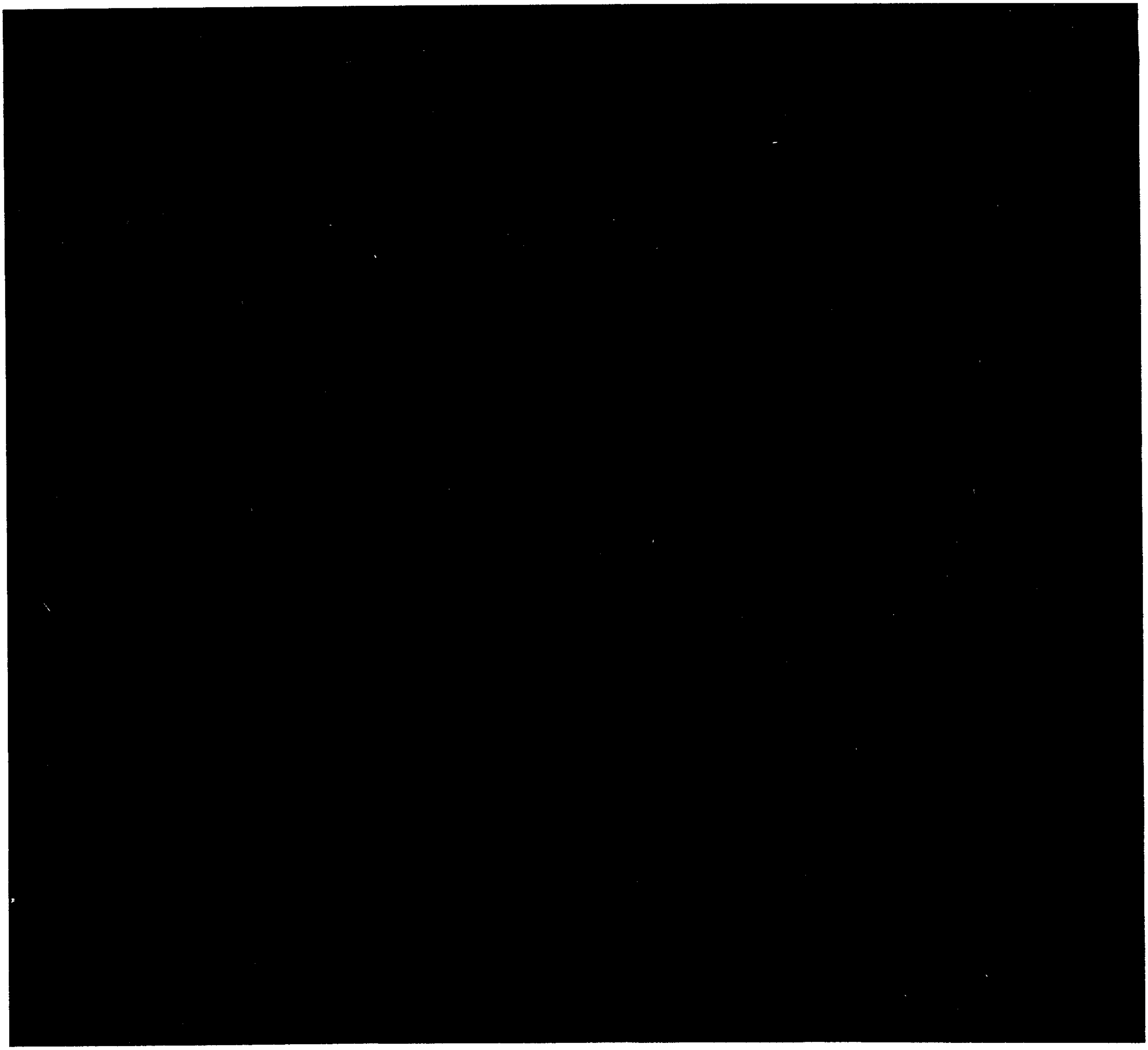

Figure A-2. Axial Stress Difference Versus Strain for [redacted] From Well No. 59 — Specimen WG/59/35/2-1/1.

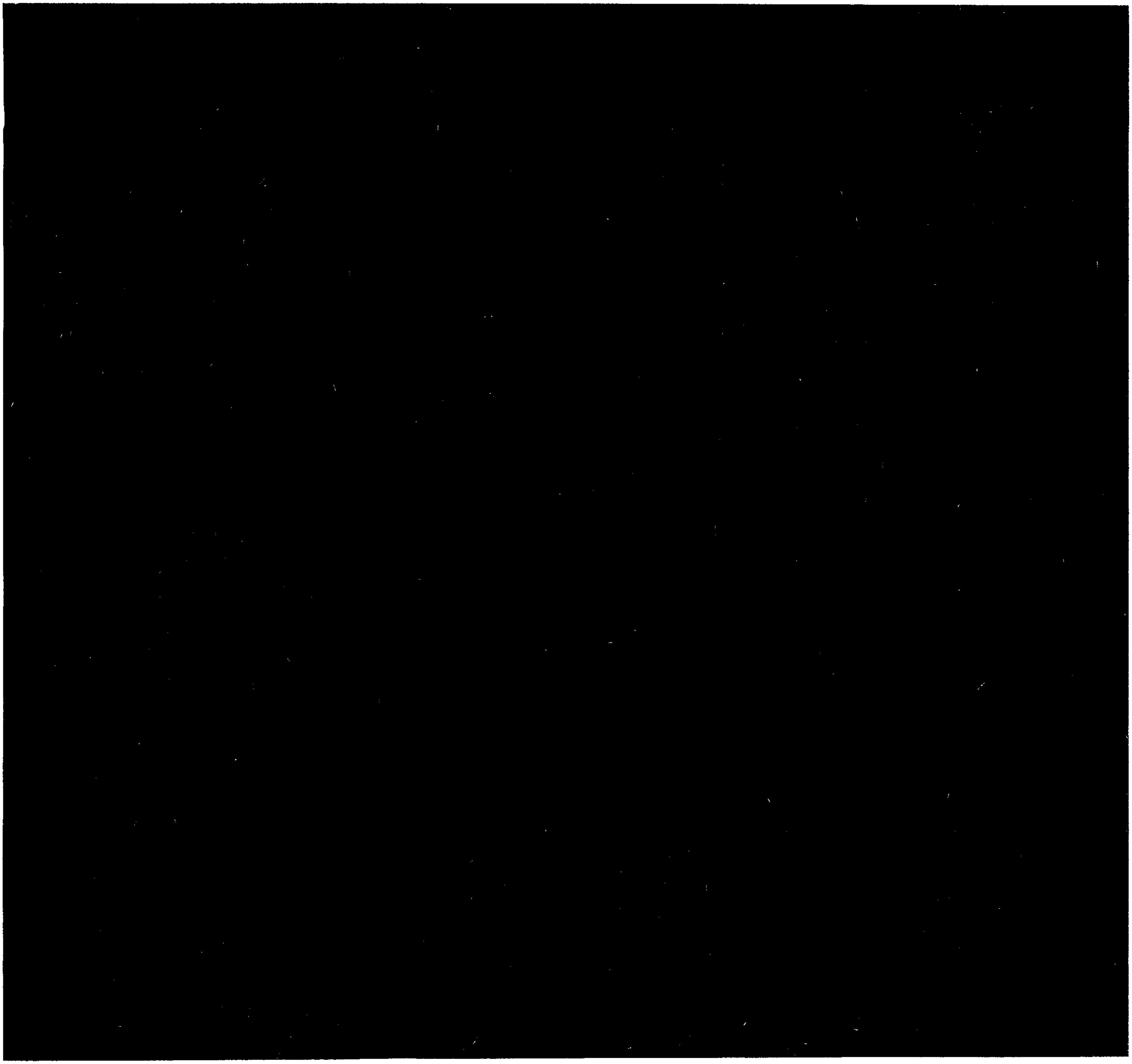

Figure A-3. Axial Stress Difference Versus Strain for [redacted] From Well No. 59 — Specimen WG/59/35/3-1.

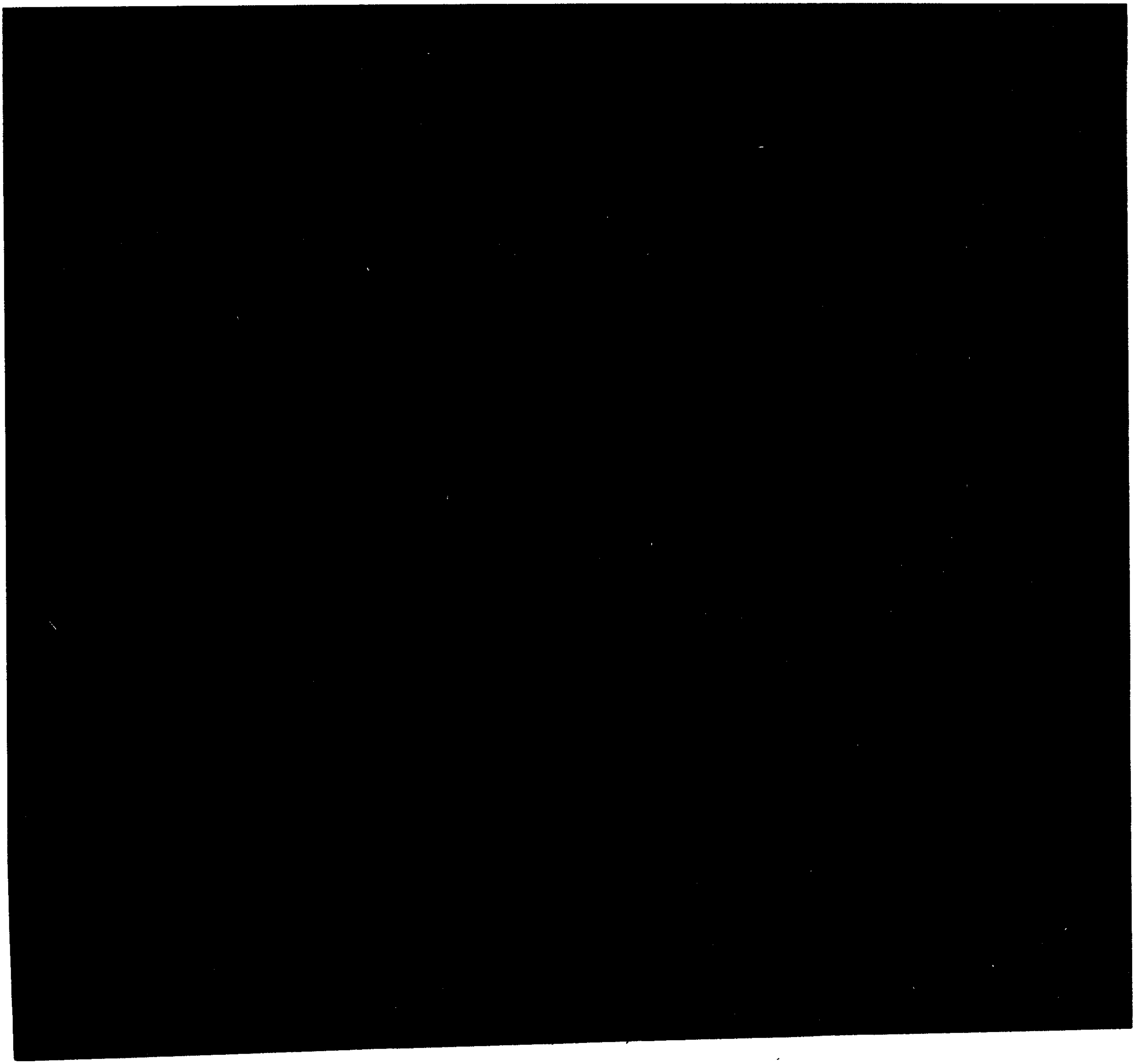

Figure A-4. Axial Stress Difference Versus Strain for [redacted] From Well No. 59 — Specimen WG/59/52/7-1/1.

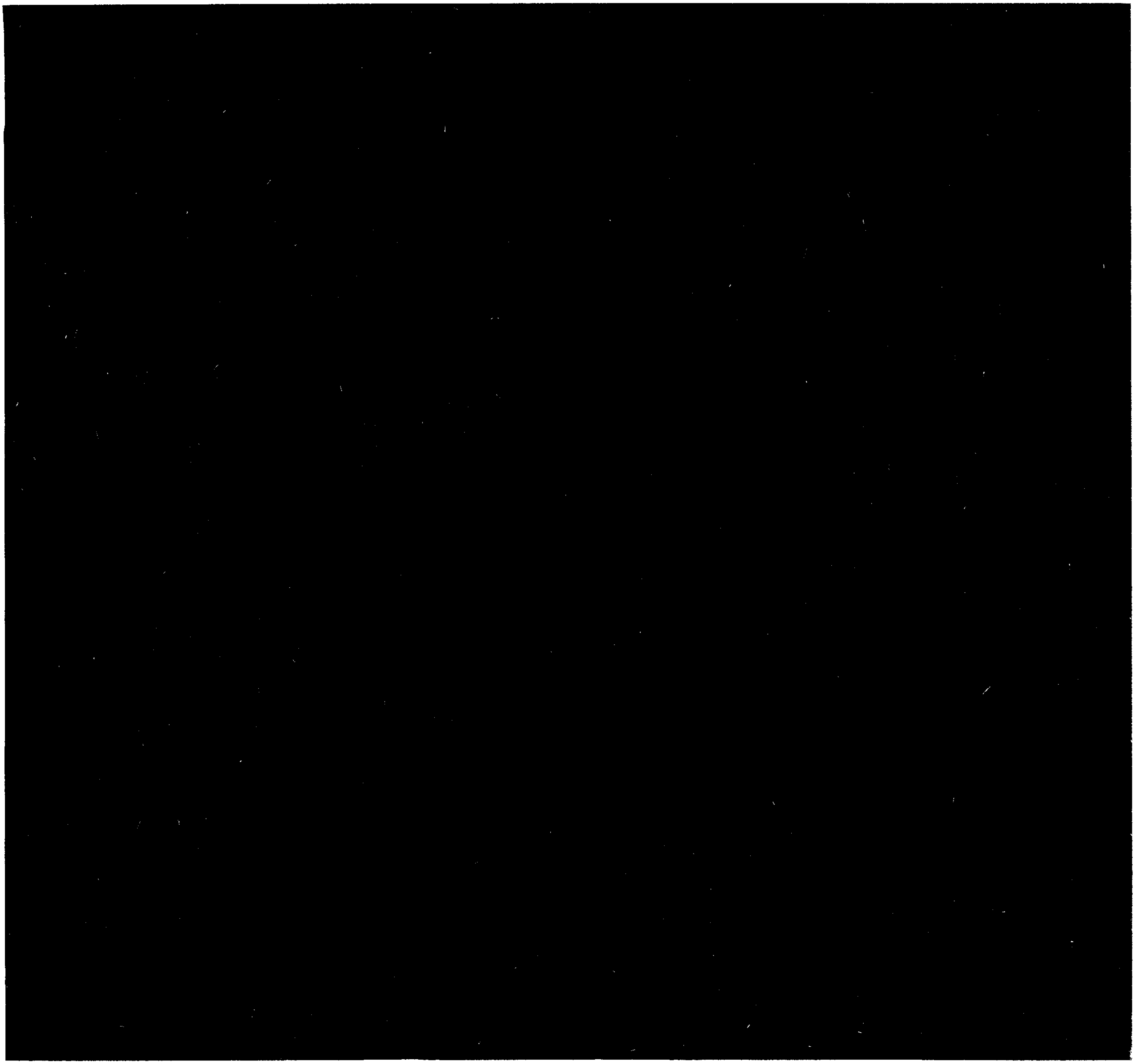

Figure A-5. Axial Stress Difference Versus Strain for [redacted] From Well No. 59 — Specimen WG/59/52/5-1.

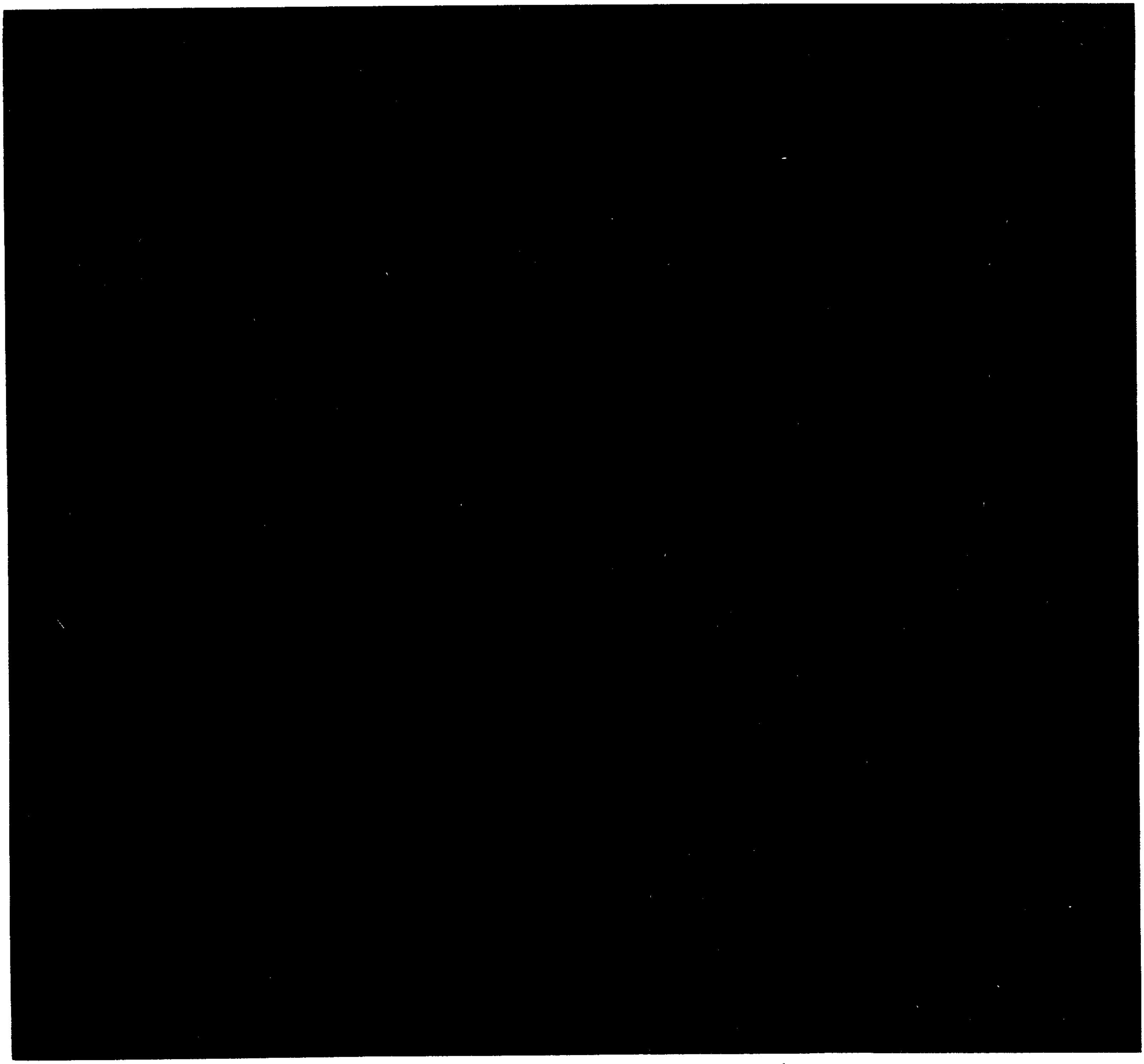

Figure A-6. Axial Stress Difference Versus Strain for [redacted] From Well No. 59 — Specimen WG/59/52/6-1.

APPENDIX B

STRESS-STRAIN PLOTS FOR CONFINED QUASI-STATIC COMPRESSION TESTS ON SALT FROM WELL NO. 58 AND WELL NO. 59

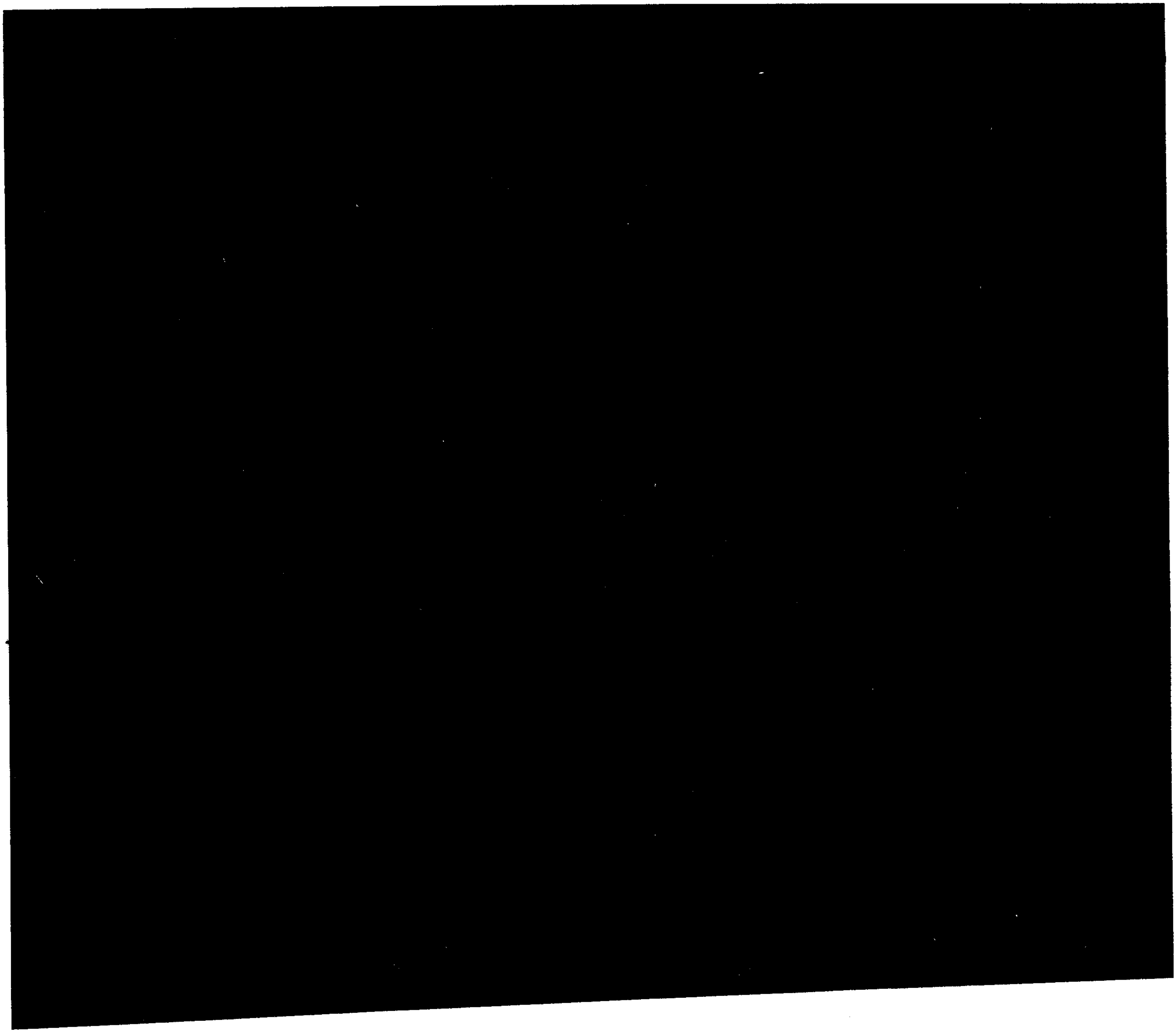

Figure B-1. Axial Stress Difference Versus Strain Difference and Volumetric Strain for Well No. 58 Salt — Specimen WG/58/4/1.

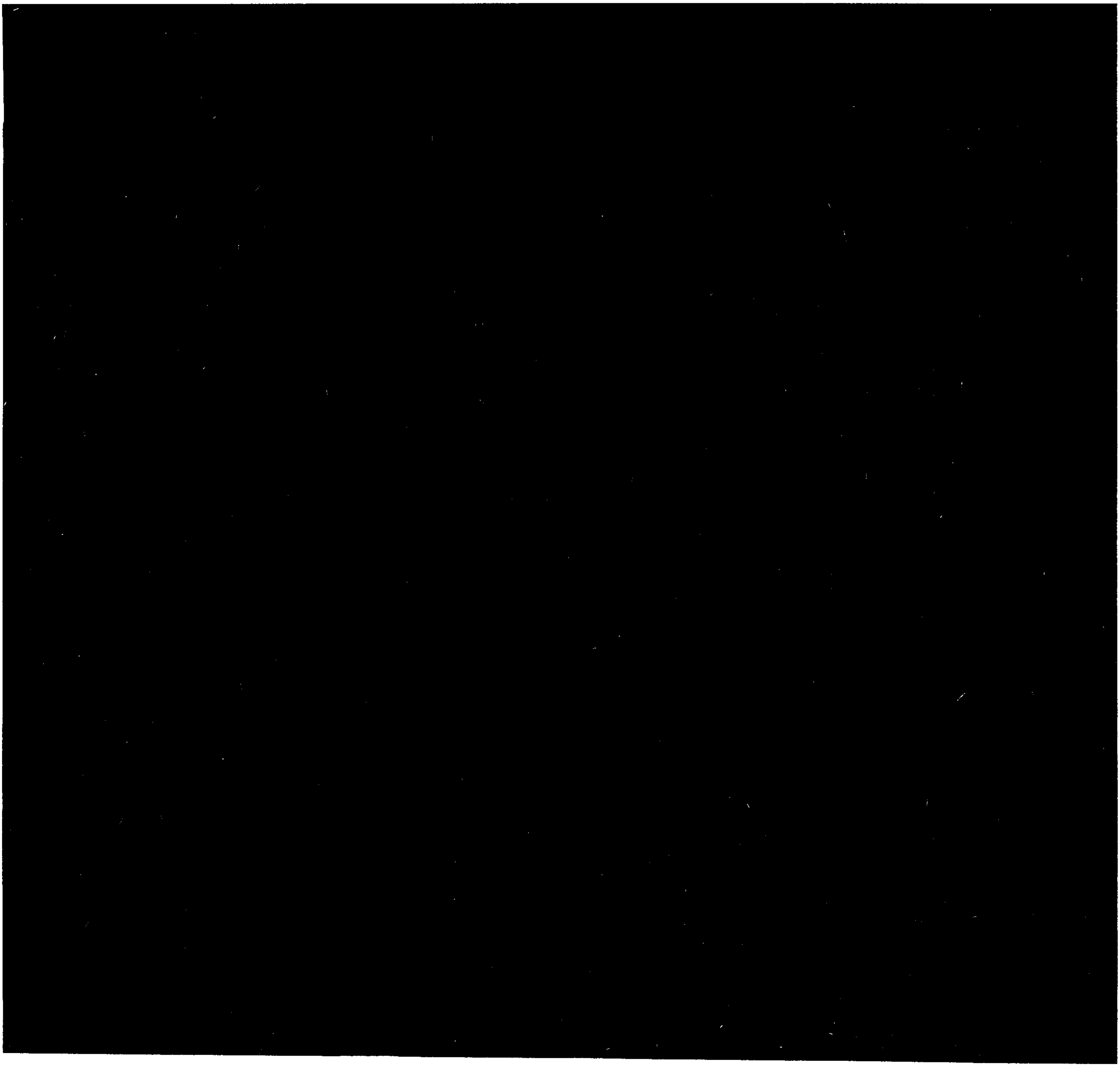

Figure B-2. Axial Stress Difference Versus Strain Difference and Volumetric Strain for Well No. 58 Salt — Specimen WG/58/6/1.

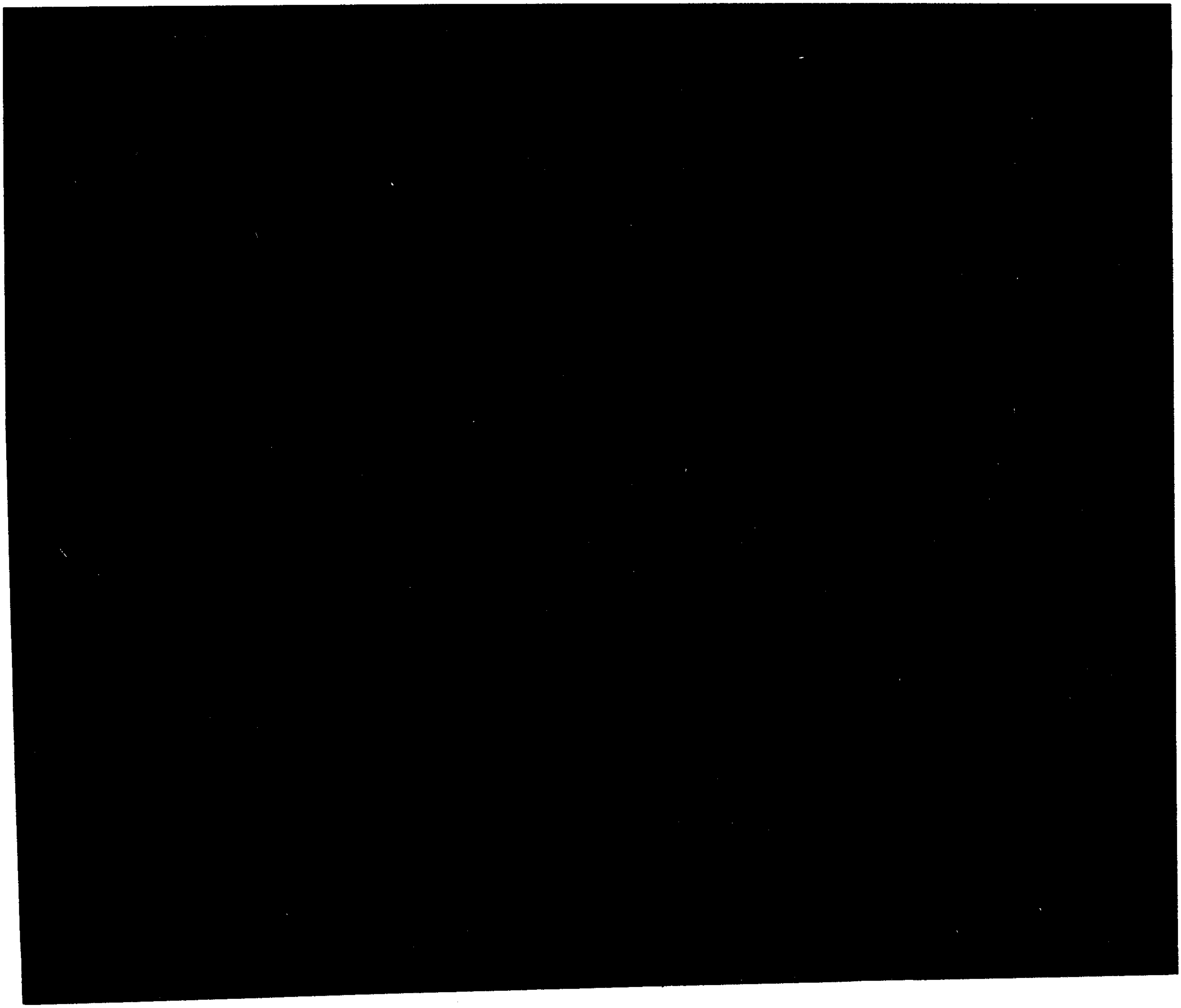

Figure B-3. Axial Stress Difference Versus Strain Difference and Volumetric Strain for Well No. 58 Salt — Specimen WG/58/6/2.

[redacted]

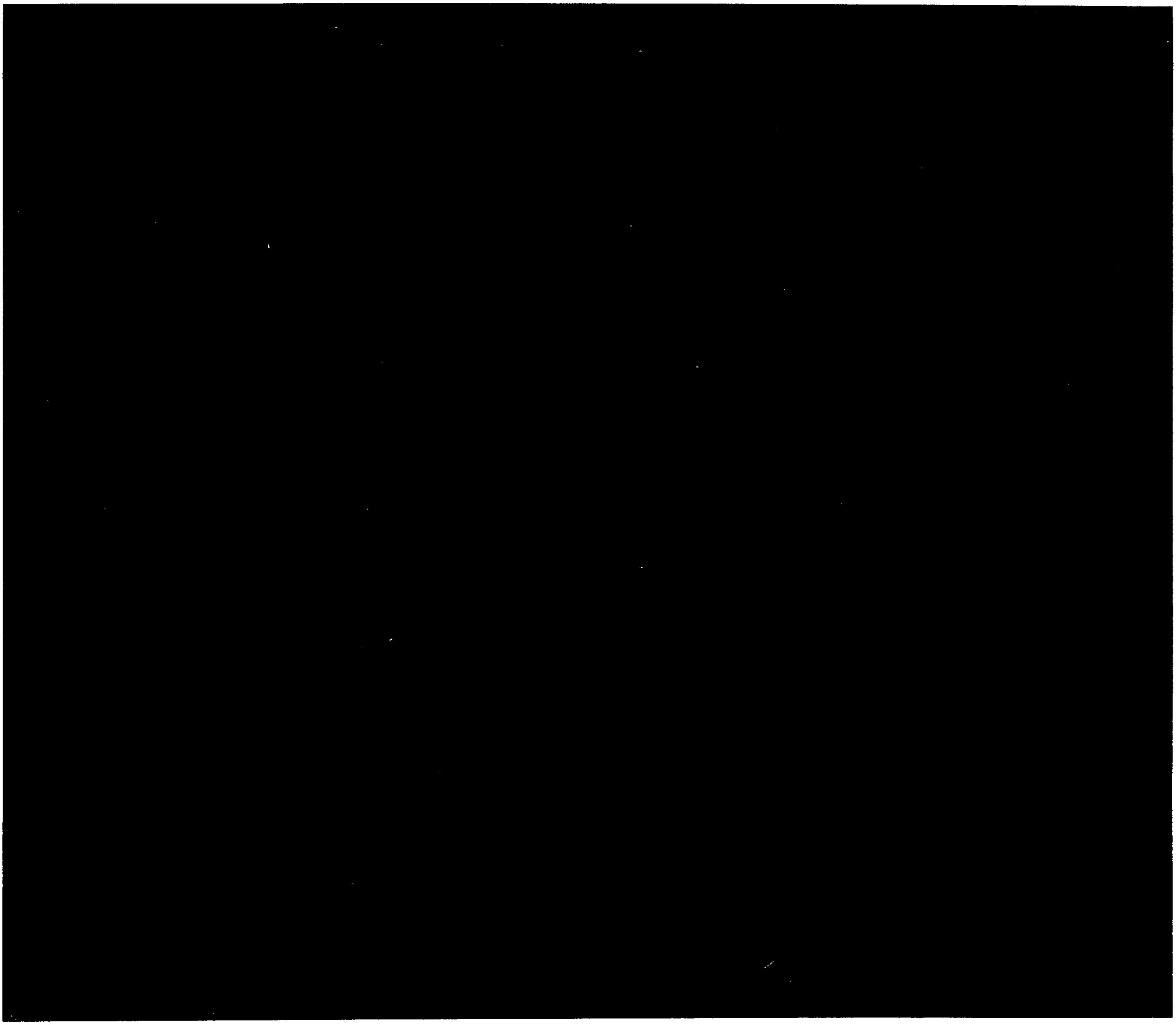

Figure B-5. Axial Stress Difference Versus Strain Difference and Volumetric Strain for Well No. 59 Salt — Specimen WG/59/77/4.

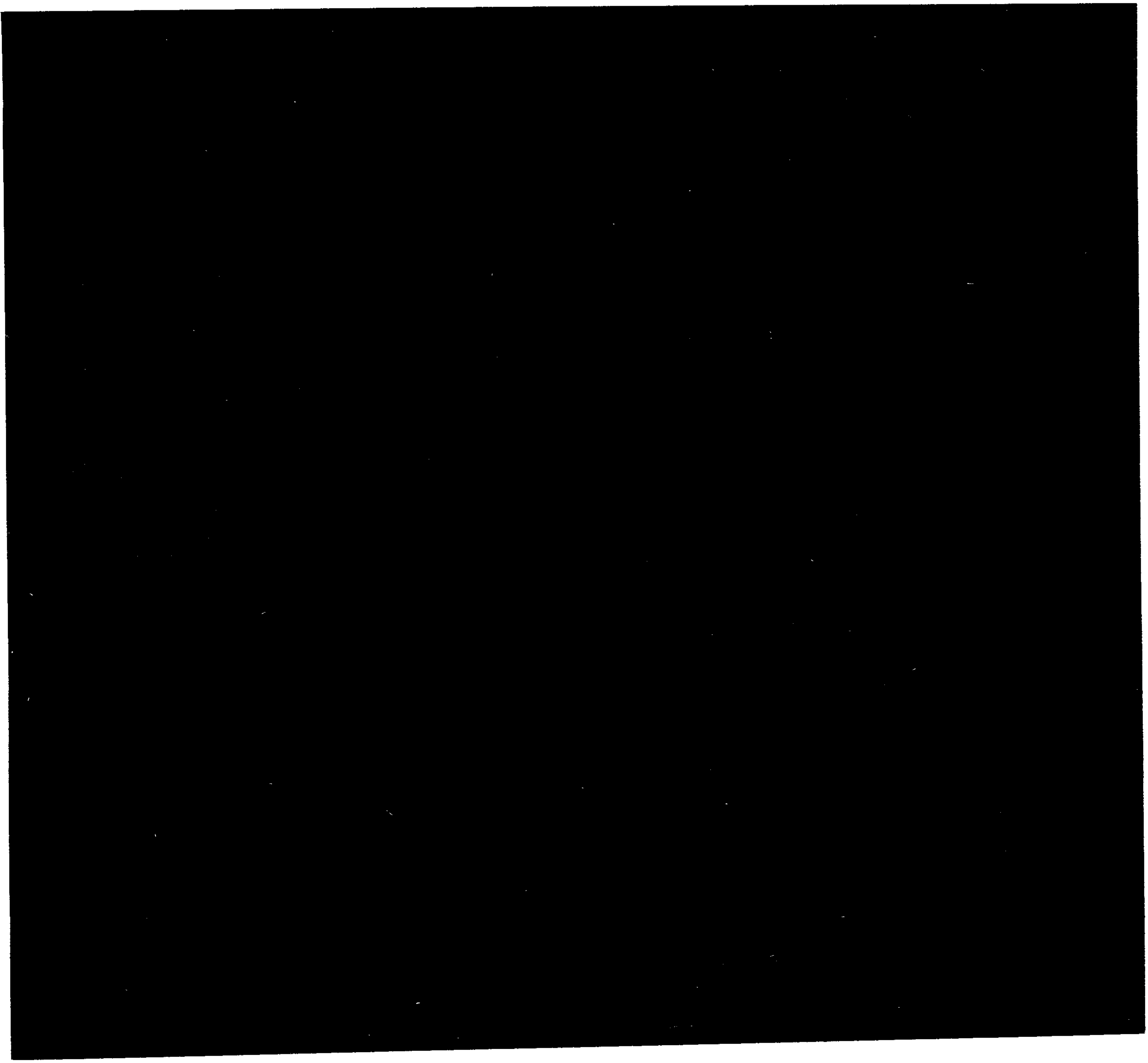

Figure B-6. Axial Stress Difference Versus Strain Difference and Volumetric Strain for Well No. 59 Salt — Specimen WG/59/78/7.

APPENDIX C

AXIAL, RADIAL, AND VOLUMETRIC STRAINS FOR CONFINED CREEP TESTS ON SALT FROM WELL NO. 58 AND WELL NO. 59

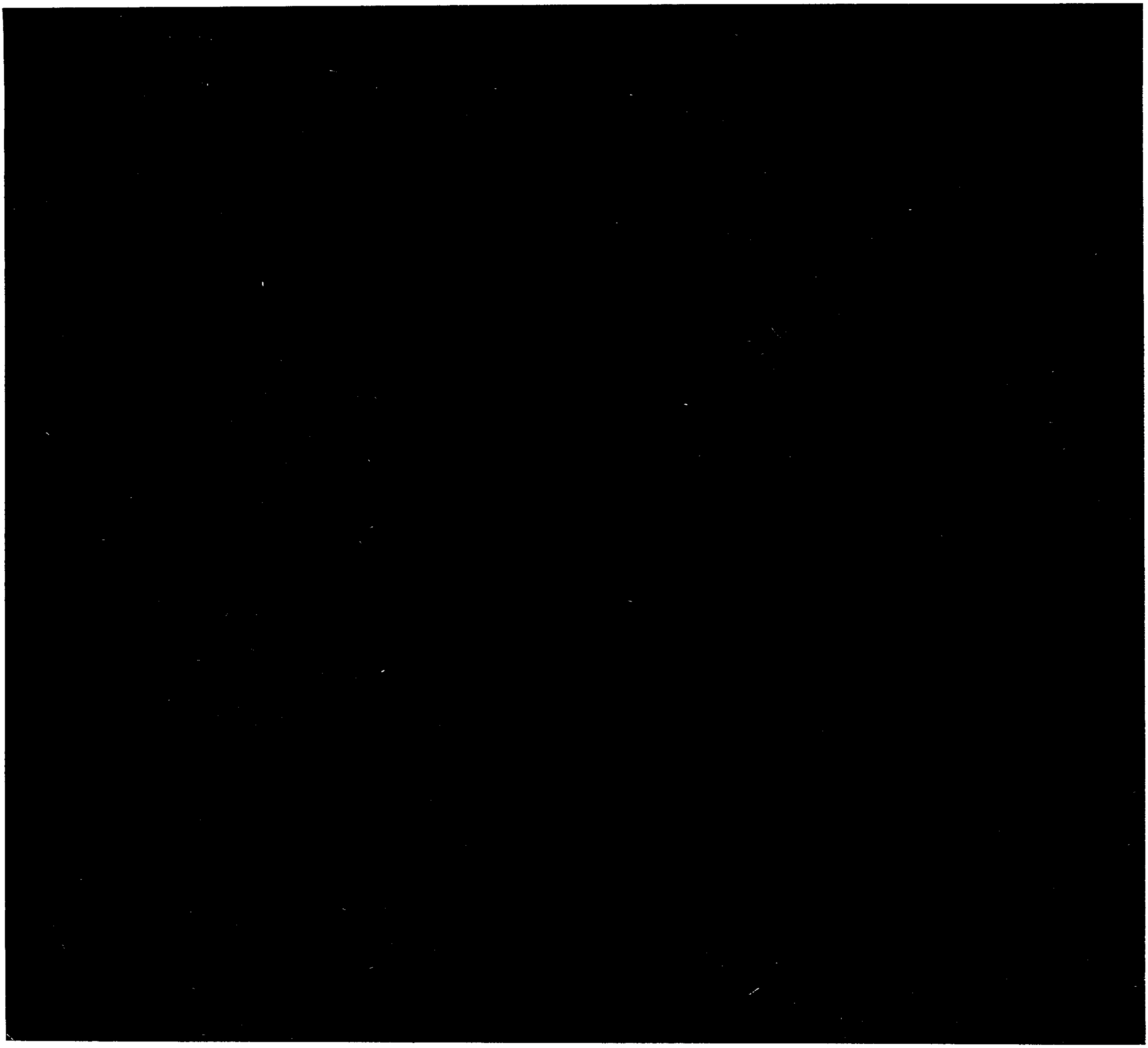

Figure C-1. Axial, Radial, and Volumetric Creep Strains for Well No. 58 Salt — Specimen WG/58/7/1.

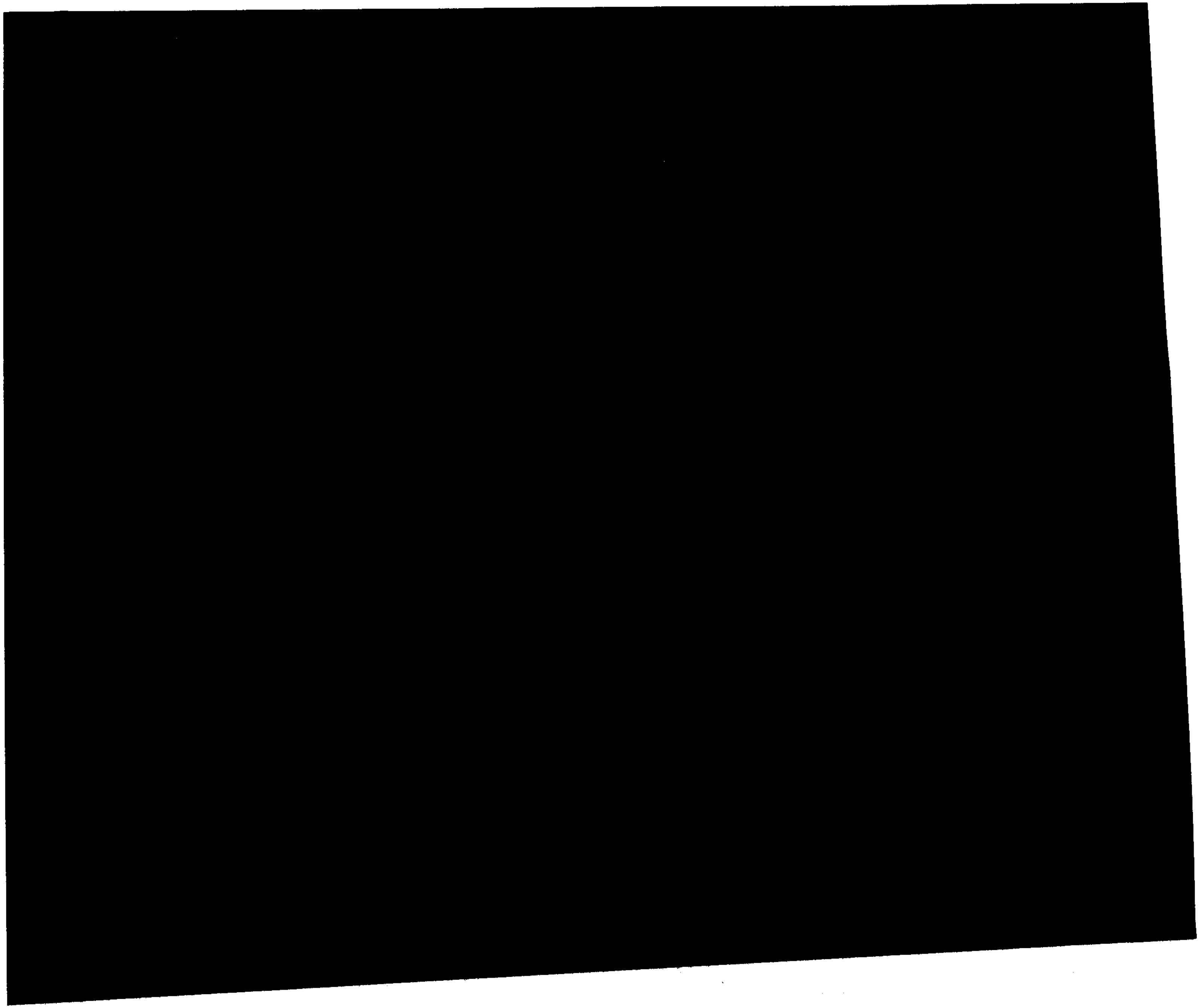

Figure C-2. Axial, Radial, and Volumetric Creep Strains for Well No. 58 Salt — Specimen WG/58/7/3.

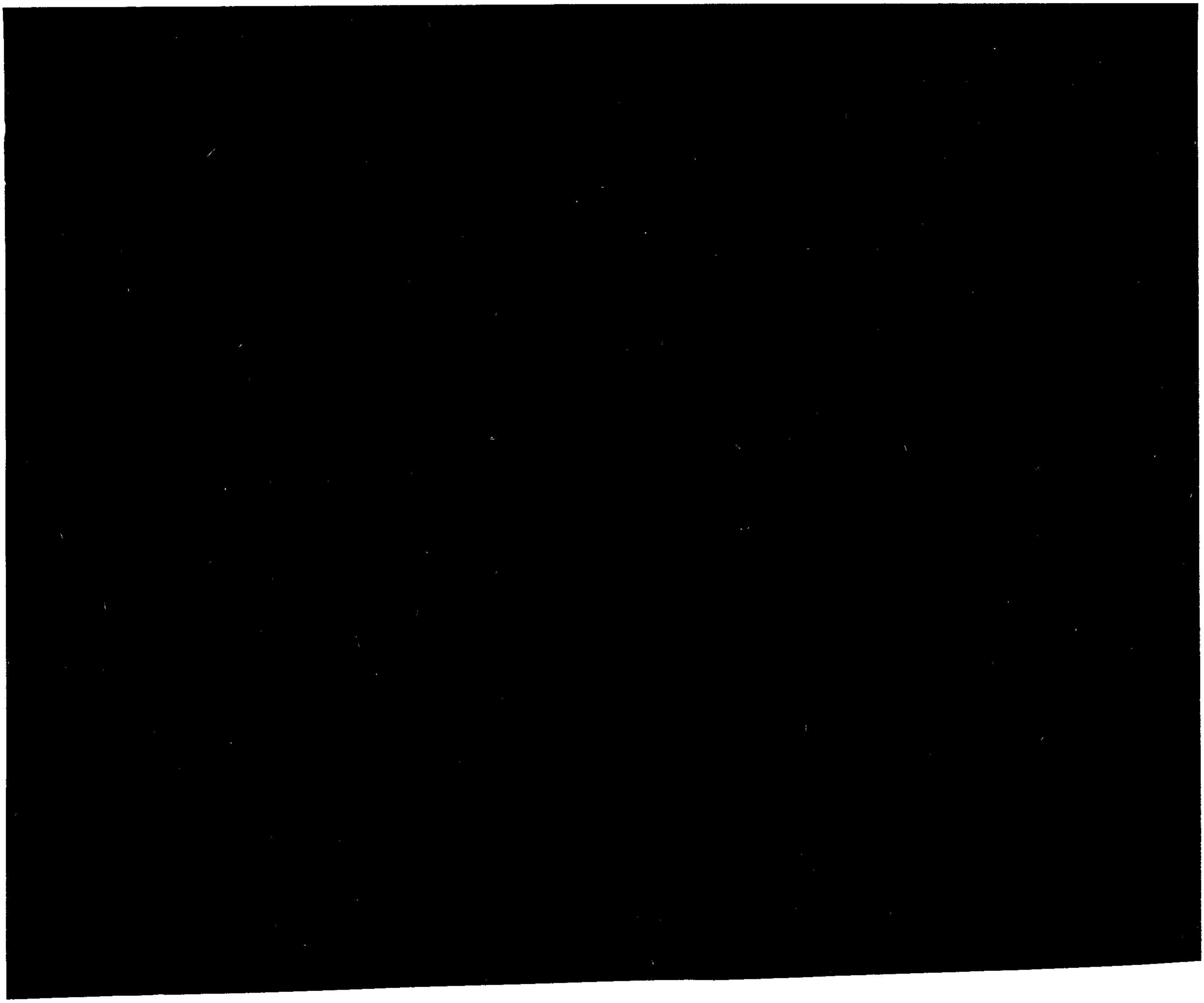

Figure C-3. Axial, Radial, and Volumetric Creep Strains for Well No. 58 Salt — Specimen WG/58/7/2.

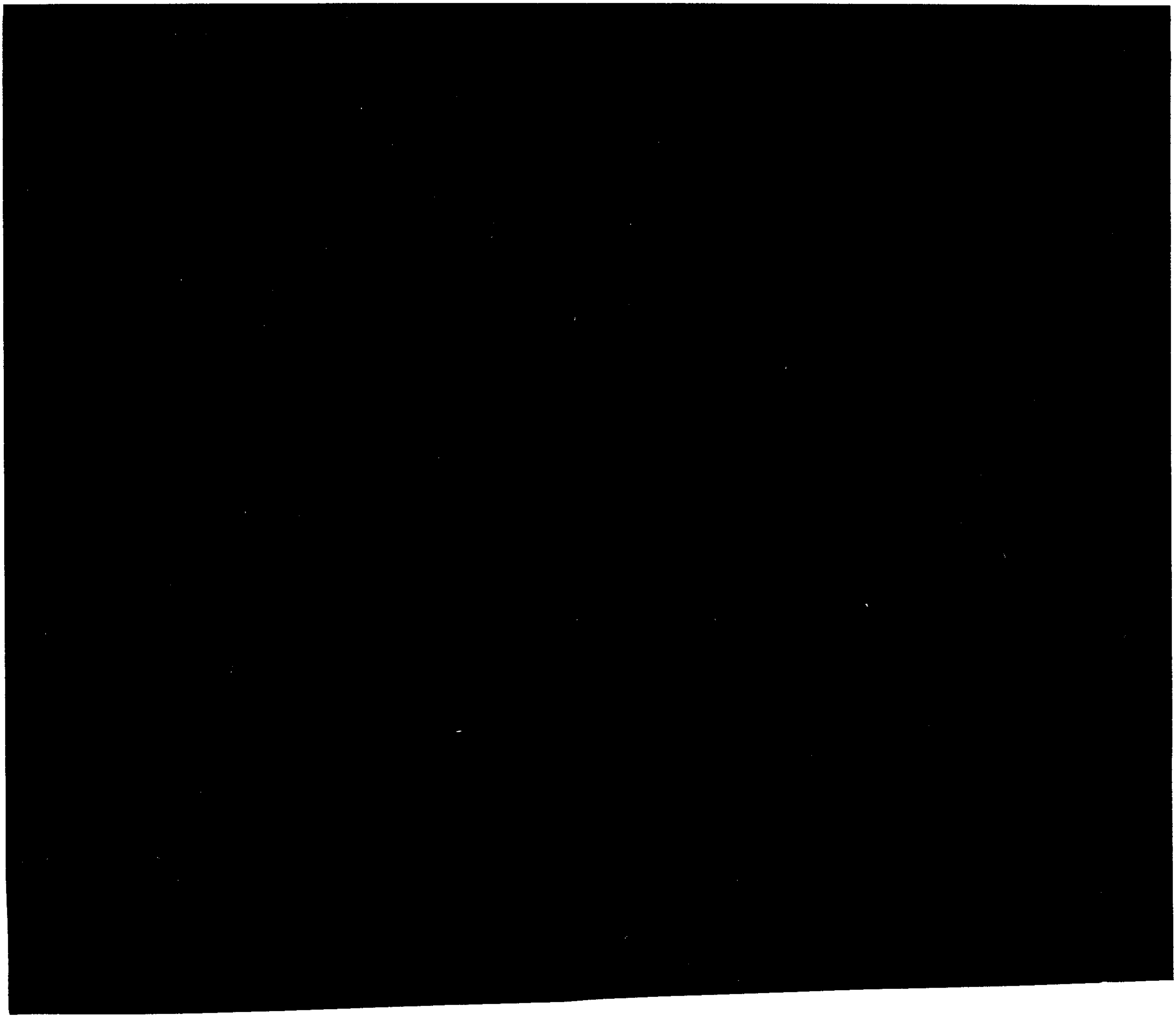

Figure C-4. Axial, Radial, and Volumetric Creep Strains for Well No. 59 Salt — Specimen WG/59/77/2.

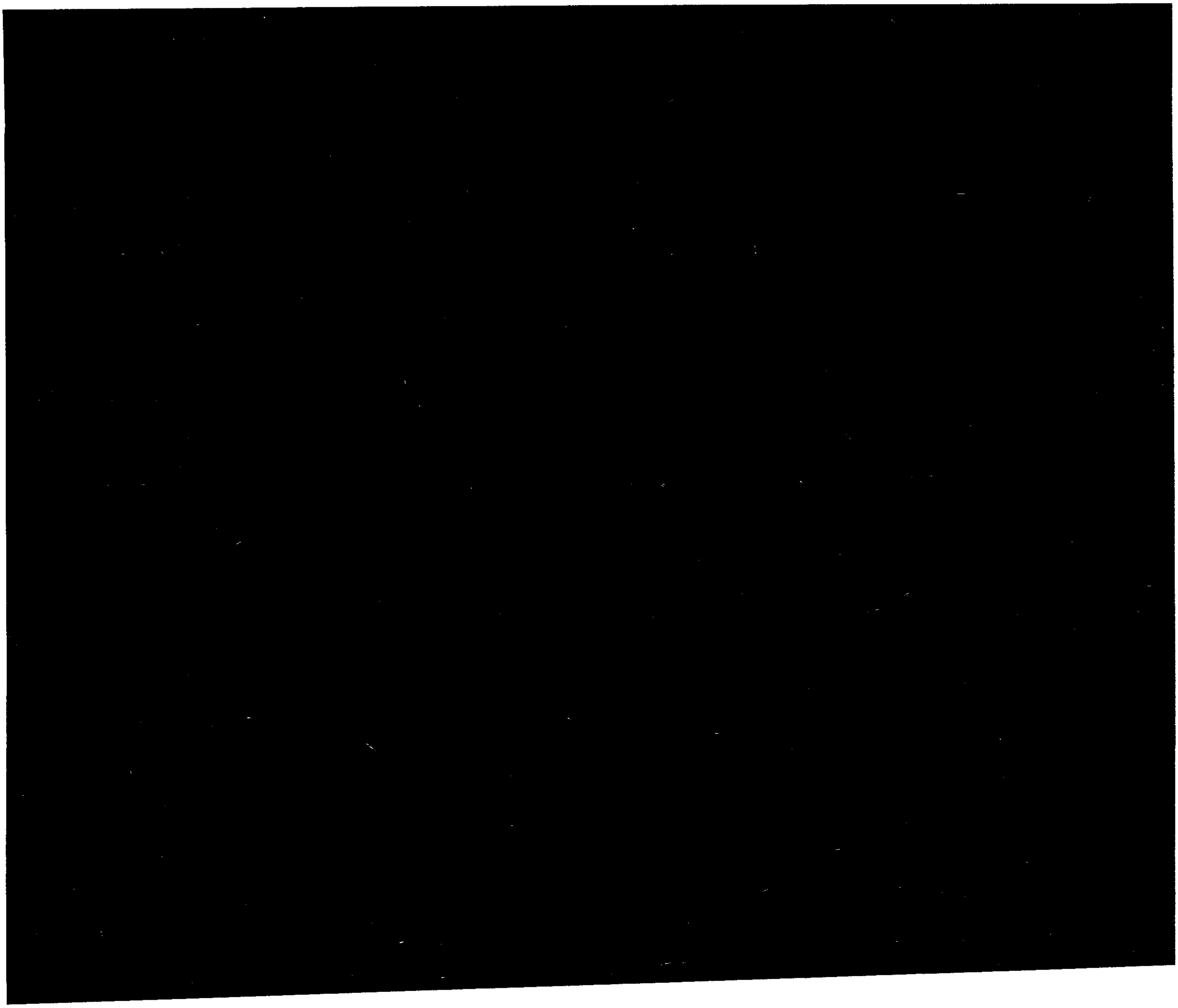

Figure C-5. Axial, Radial, and Volumetric Creep Strains for Well No. 59 Salt — Specimen WG/59/77/3.